THE PETROLOGY OF THE STEVENS PASS-NASON RIDGE AREA, WASHINGTON

by

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A thesis submitted in partial fulfillment for the degree of

MASTER OF SCIENCE

UNIVERSITY OF WASHINGTON

1951

ACKNOWLEDGMENT

I am deeply grateful to Dr. Peter Misch who supervised my work and offered friendly and invaluable criticism. I wish to thank Dr. Howard A. Coombs for his valuable advice and constant encouragement. I also wish to acknowledge the encouragement and the numerous courtesies of Professor George E. Goodspeed, Executive Officer of the Department of Geology.

I wish to thank Mr. Ray Sleeper, a student in the Department of Geology, for being an enthusiastic field assistant during the summer of 1950. Finally, it is a pleasure to acknowledge the courtesies extended to me by the Rangers of the U.S. Forest Service, Leavenworth District, Chelan National Forest. In particular, I am indebted to Rangers Estes Kester and Gordon Sanford.

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INTRODUCTION

Location and Accessibility

The Stevens Pass-Nason Ridge area lies on the summit of the Cascade Range, approximately half way between the Puget Sound lowland on the west and the Columbia Plateau on the east (cf., Fig. 1). The center of this area is approximately 60 miles east of Seattle. This area is traversed by U.S. Highway 2, the northernmost route of travel across the Cascade Range of Washington. Plate A is a topographic map of this area.

Most of the area thus far mapped lies east of the Cascade Crest and occupies portions of two United States Geological Survey topographic quadrangles--the Skykomish and the Chiwaukum (17). The western boundary of the area studied

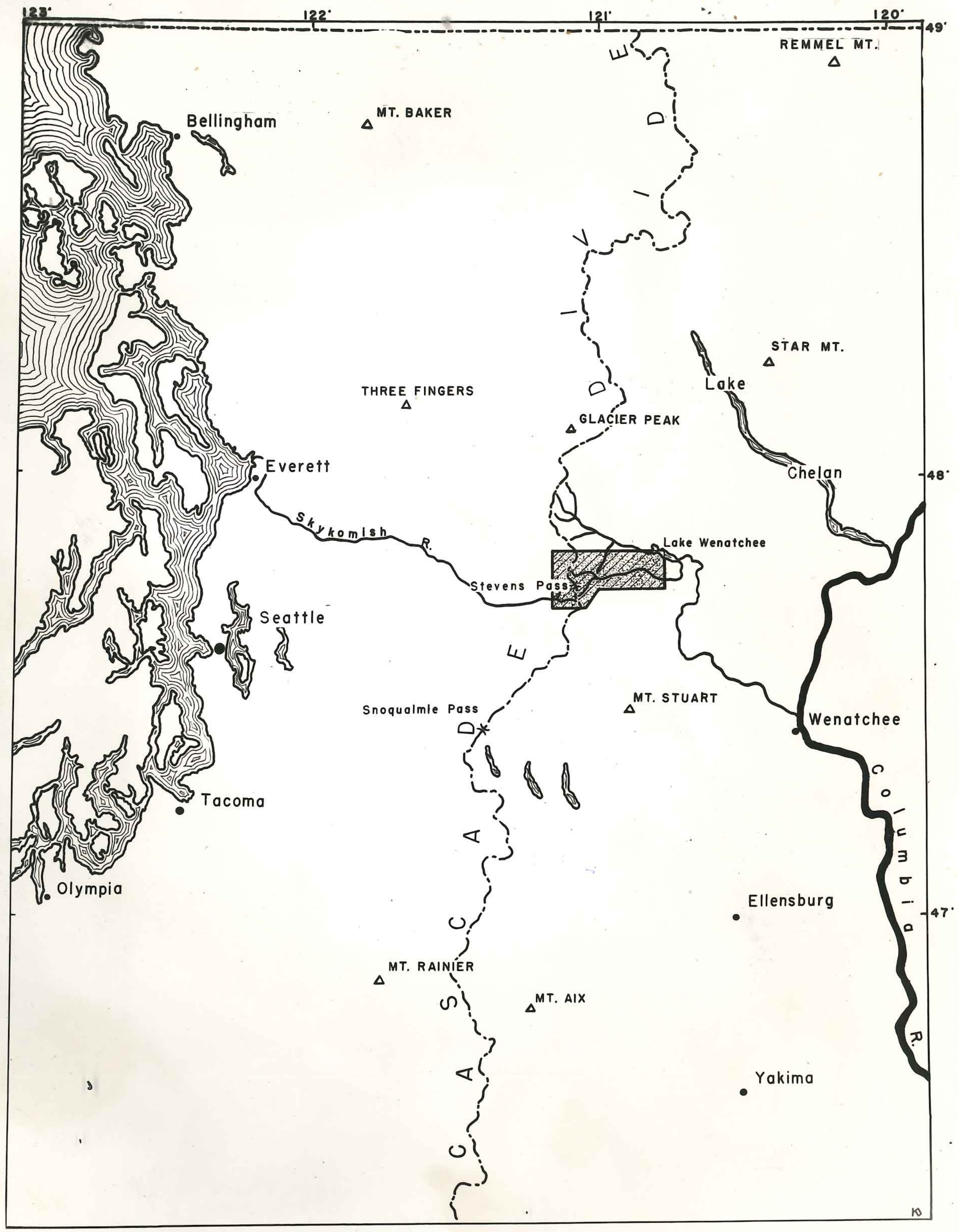


Figure I.—Index map of the northern Cascades showing the location of the Stevens Pass—Nason Ridge Area passes through Scenic, the highest inhabited place in the Skykomish valley, which is four miles west of Stevens Pass. The eastern boundary is near Lake Wenatchee, approximately 15 miles east of the Crest.

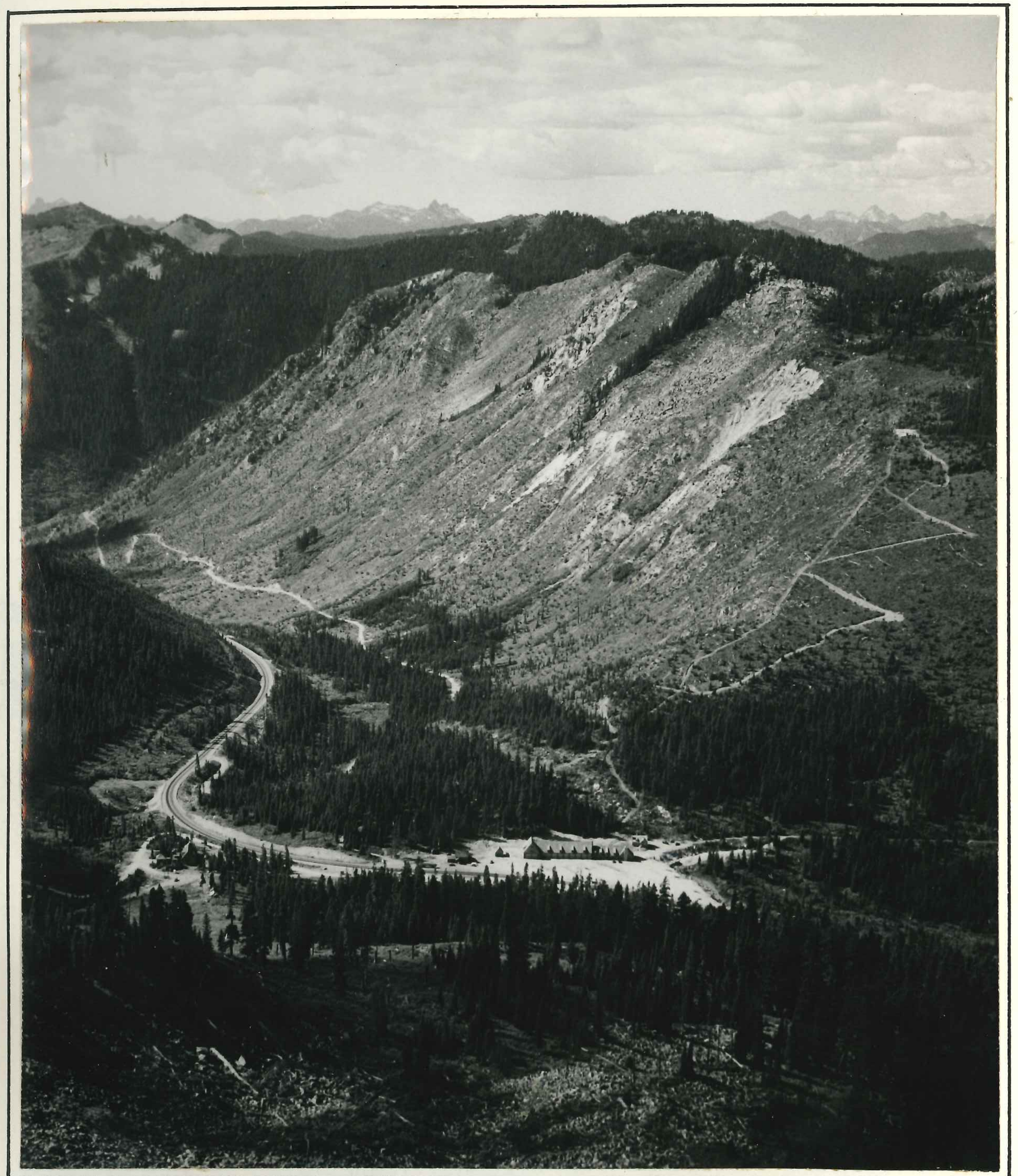
Apart from U.S. Highway 2 the only other roads are an often impassable Bonneville Power Administration maintenance road along Mill and Tunnel Creeks, and a logging road up the Little Wenatchee River. The Great Northern Railway's famous Cascade Tunnel lies beneath Stevens Pass. The Cascade Crest Trail follows the divide in this area. Other trails are few and usually poorly maintained.

Topography and Drainage

The entire area is mountainous and has considerable relief (Plates I, II, and III). Near Stevens Pass there is no predominant trend to the ridges. Peaks and ridges in this vicinity rise to a maximum elevation of about 6000 feet, with a maximum relief of about 3000 feet. East of Stevens Pass the topographic units assume an east-west trend, with maximum elevations exceeding 7500 feet, and a maximum relief approaching 6000 feet. Glacial cirques, often occupied by small lakes, are common, and all the major valleys are glacial troughs.

The two major streams east of the divide are Nason Creek and the Little Wenatchee River. All the eastward

PLATE I



Stevens Pass and the avalanche-swept south slope of Skyline Peak, as seen from the main peak of Mt. Fernow. Peaks of the Index and Monte Cristo areas form the skyline.

PLATE II

Granitic mountains near Stevens Pass. Lichtenberg Mt. lies at extreme right. Part of Skyline Mt. is in the foreground. The horn of Sloan Peak (7,790 feet) lies in the middle distance. View is northwest from the main peak of Mt. Fernow.

PLATE III

The bare granitic slopes of Lichtenberg Mt. occupy the center of the picture. The Cascade Crest takes a serpentine course to the north, passing just right of Glacier Peak, a major Cascade volcano. View looking north from the main peak of Mt. Fernow.

drainage joins the Wenatchee River which flows into the Columbia River just north of the city of Wenatchee. The drainage of the western side eventually joins the Skykomish River which empties into Puget Sound near the city of Everett.

Previous Geologic Investigations

Geologically, most of the northern Cascades is unknown, though certain restricted areas have been studied. Previous work in the area described in this paper has been in the nature of general reconnaissance only and has not been published apart from being used in the compilation of the Geologic Map of the State of Washington (2,3). This map gives the approximate distribution of the granitic and metamorphic rocks in this area, although the actual boundaries shown are incorrect.

Some additional geologic work has been done in adjacent areas. Before the turn of the century I. C. Russell made several reconnaissance trips in areas to the east and northeast (8,9). To the west of the area described in the present paper, W. S. Smith made a brief petrographic and physiographic study of the Skykomish River basin (13,14,15). To the southeast of the present area, in the vicinity of Chiwaukum Creek, B. M. Page has done work involving structure, petrology, and physiography (7). In an extensive region east of the Stevens Pass-Nason Ridge area, C. L. Willis has done detailed work in structure and petrology, the results of which have been published in his recent University of Washington doctorate thesis (20).

Field Conditions

The conditions for geologic investigation in the present area are not ideal but are far better than in most parts of the Northern Cascades, chiefly owing to the presence of U.S. Highway 2. Dense timber and brush cover the lower elevations in the western part of the area. In the eastern part, however, the ground, though timbered, is more open. High, rugged peaks and ridges offer excellent, though not by any means always continuous, exposures. The relief approaches, in some places, 6000 feet, and most of the slopes are very steep. Heavy snows of up to 700 inches in one season prohibit geologic work except during the short summer season.

I spent eight weeks in the field during the summers of 1949 and 1950. Due to a lack of aerial photographs, the mapping had to be done by Brunton compass traverses aided by photographically-enlarged copies of the Chiwaukum and Skykomish quadrangles of the U.S. Geological Survey. Over 300 specimens were collected, from which thin sections were made.

GEOLOGY AND PETROLOGY OF THE CRYSTALLINE ROCKS

General Statement

Though the Cascades are a topographic unit, their rocks vary greatly in different parts of the Washington section of the range. South of Snoqualmie Pass (Fig. 1), which lies approximately 30 miles southwest of Stevens Pass, the bulk of the exposed rocks are Tertiary volcanics (2,12). North of Snoqualmie Pass the Cascades are a complex mass of metamorphic, sedimentary, and igneous rocks, dominantly of pre-Tertiary age. The rocks described in this paper are mainly metamorphic and granitic rocks of this northern province.

The rocks of the Stevens Pass-Nason Ridge area readily permit a threefold division, both geographically and petrographically (Plate B). The western third of this area, lying both east and west of Stevens Pass and thus straddling the crest of the Cascades, is dominantly composed of granitic rocks, the most abundant type being a quartz diorite. The central third of the area is a series of extremely contorted schists which are the oldest rocks present. The eastern third of the area, extending to Lake Wenatchee, consists of a belt of granitic and mixed gneisses.

The petrologic and structural description of these rock units is given in chronological sequence.

Schists

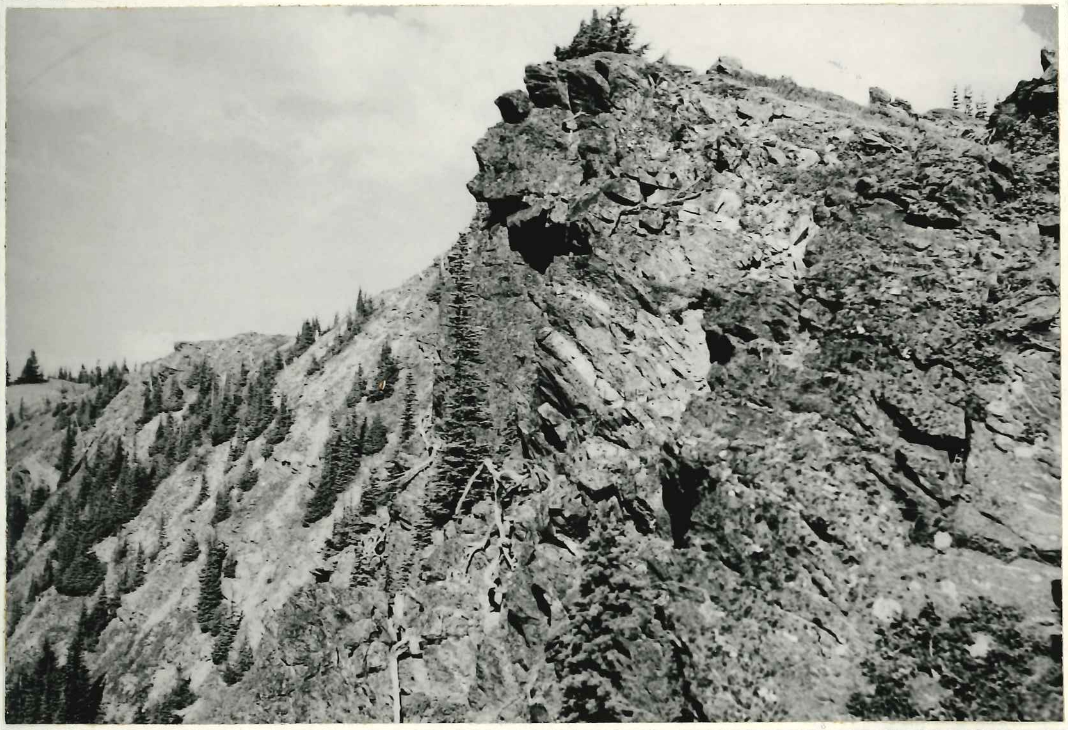
Distribution and Structure

The oldest rocks of the Stevens Pass-Nason Ridge area are a group of schists. They are found in a broad belt east of Stevens Pass between the granitic rocks lying west of Berne and the gneisses lying east of Merritt (Plates A and B). The maximum width of this belt, as measured across the strike, is six miles. The prevailing strike of these schists is northwest-southeast, and this belt was followed along the strike for four miles to the southeast and ten miles to the northwest from the Stevens Pass Highway (U.S. 2). Only further regional mapping will determine the northwest and the southeast terminations of this unit. However, Dr. Peter Misch says that he has observed the same schist unit about 30 miles to the northwest in the Whitechuck River valley west of Glacier Peak (17), and Page (7) has observed similar schists approximately ten miles to the southeast in the vicinity of Chiwaukum Creek.

In spite of the timber cover at the lower elevations, exposures are generally very good. Also, there are numerous road and railway cuts along Nason Creek. At the higher elevations cliffs and sharp ridges offer almost continuous exposures in the schists. These schists form the highest elevations in the entire area. Prominent among the higher peaks are the Chiwaukum Mountains, lying south of Nason Creek, which attain elevations in excess of 8000 feet. The schists also form the bulk of Nason Ridge, including Mt. Howard (7520 feet) and Rock Mt. (7300 feet). The schists also form some of the lowest elevations in the entire area, being found at elevations less than 2000 feet. The northern ridge of the Chiwaukum Mountains consists of schist forming a series of very steep, north-facing cliffs and narrow, sloping benches. Even more spectacular than this face is the north side of Nason Ridge which overlooks the Little Wenatchee River. Here is a wall which, in many places, is a mile high--a wall of nearly vertical cliffs and inclined benches. The southerly slopes of the Chiwaukum Mountains and of Nason Ridge are considerably less steep. Every ridge in the schists displays this asymmetery which is probably due to glacial action locally aided by structural control (Plate IV).

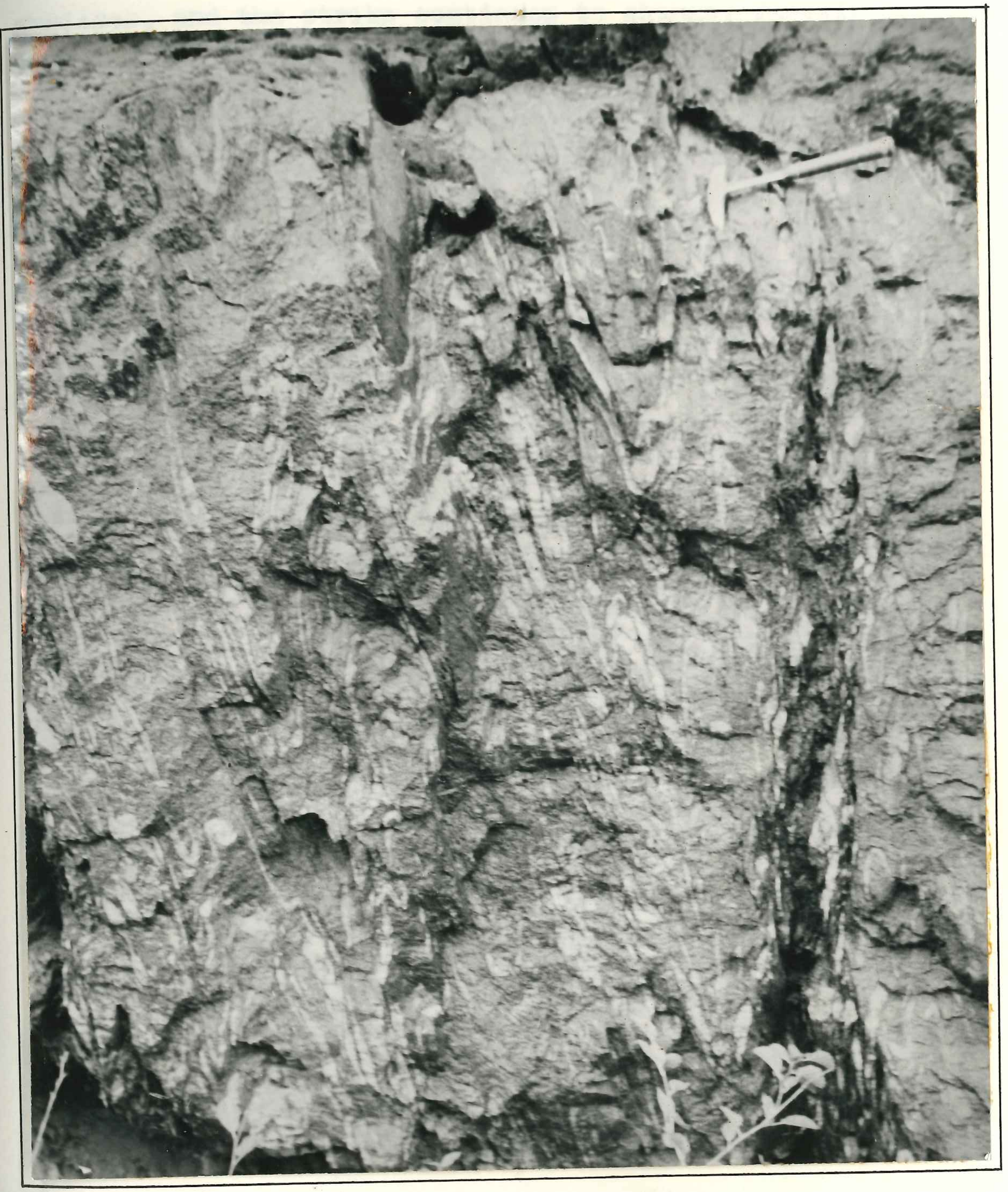
The predominant strike in the schists is approximately northwest-southeast (Plate B). In the western part of the schists they are invariably found in isoclinal folds which are readily seen in the field, and it is presumed that any larger structures present are also isoclinal folds. These folds generally have a steep dip to the northeast (Plate V). Near Merritt the strike swings around to nearly east-west, and the dips become more gentle and, though variable, are generally to

PLATE IV



Asymmetry of strike ridges in schists. The steeper face to the left is at the head of a cirque; the more gentle slope to the right is a dip slope. North ridge of Mt. Fernow.

PLATE V



Banded biotite-quartz schist. White exudation bands and lenticles of quartz mark the isoclinal folding and steep dips characteristic of these schists. Immediately west of Schilling Creek on U.S. 2.

the north. East of Merritt the schists pass into granitic gneisses, and the strike continues to change, finally becoming northeast-southwest, with moderate dips to the northwest. Field observations by Willis (20) and the author on the flanks of Dirty Face Peak northeast of Lake Wenatchee show a prevailing strike of northwest-southeast and steep southwest dips. A coordination of these data appears to indicate that a major structure--a broad northwest-plunging syncline--has been superimposed upon the isoclinally-folded schists and gneisses.

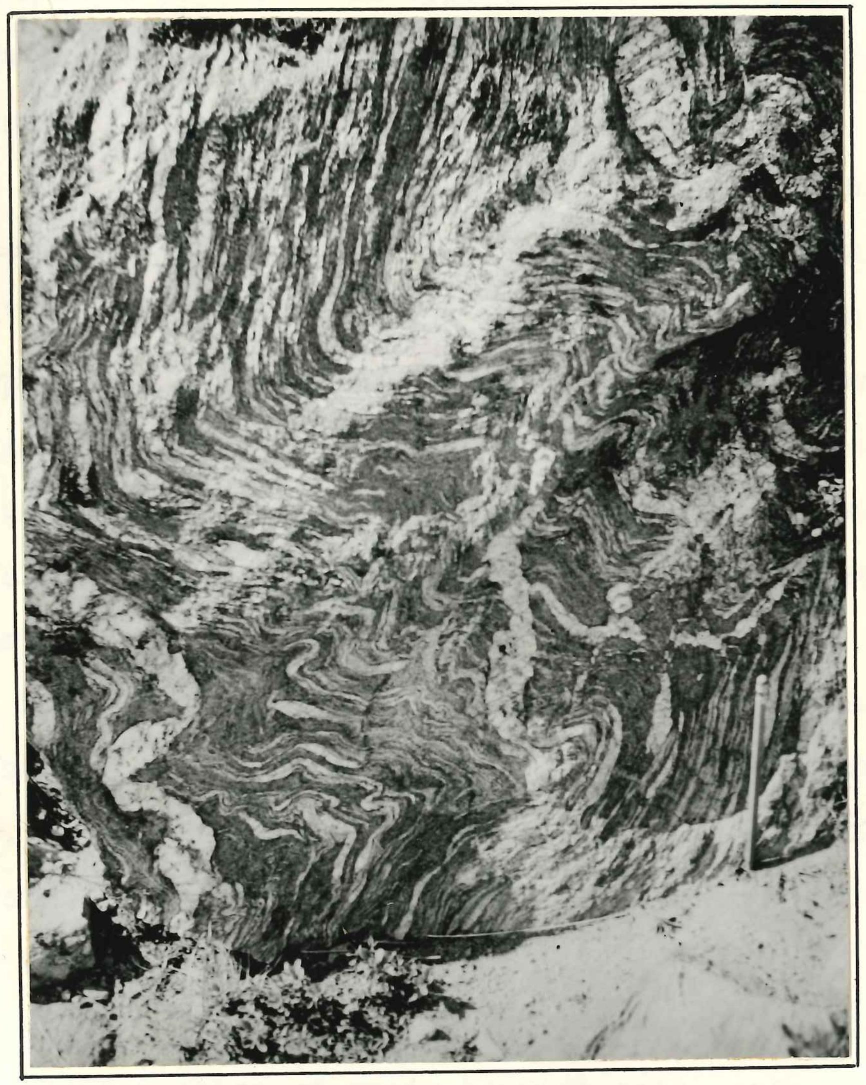
Though petrographically quite variable, in the field the schists present a rather uniform appearance, weathering usually to a dirty reddish-brown color. It is therefore difficult to distinguish different varieties of schist in the field. The various types described in succeeding pages have been differentiated by means of microscopic study.

Petrographically the schists can be divided into two major groups. The predominant type, though variable, is a biotite-quartz schist. A subordinate type, also quite variable, contains hornblende, usually in excess of the biotite.

Biotite-Quartz Schists

These schists are generally isoclinally-folded and much contorted (Plate VI). Their dips are variable, but usually steep. These schists normally exhibit megascopically-visible banding, and there are three distinct kinds of bands (Plate

PLATE VI



Banded biotite-quartz schist with intricate minor folding. Later cross-cutting quartz-feldspar replacement veins. East slope of Mt. Fernow.

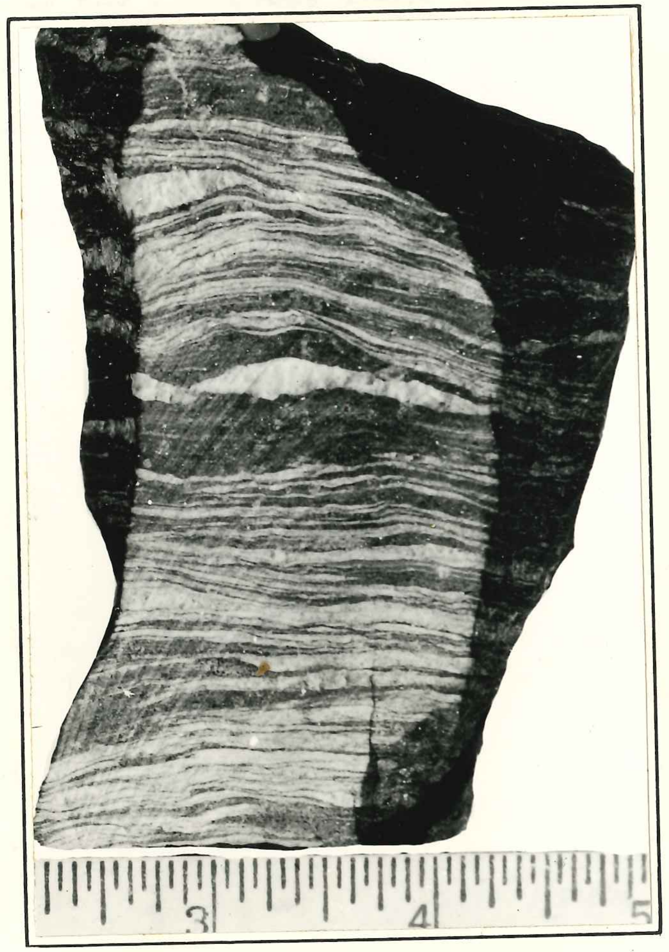
VII).

The most prominent bands, and the widest, are dominantly composed of quartz and commonly exhibit pronounced pinching and swelling. These alternate with two kinds of biotite-quartz schist: one type is a thin, greyish, very fine-grained quartz-rich band; the other is a darker, biotite-rich band.

In view of this repetition of alternating bands and lenticles, the rock might be called by some "gneissose," if Tyrrell's definition (16,p.274) were followed. However, most metamorphic petrographers do not follow this usage and would unquestionably classify these rocks as schists. Accordingly, in the present paper the term "gneiss" will be restricted to those fairly coarse-grained foliated rocks possessing a high feldspar content.

Some exposures of the schists show as many as 15 different bands within one inch, yet in others the bands are much thicker, and some of the wider quartz bands may swell to boudin-shaped aggregates up to 18 inches in thickness perpendicular to the foliation of the schist (i.e., in "c"). Such massive segregations of quartz often extend for a score of feet in the direction of their longest axis--this axis paralleling the <u>b</u>-lineation in the rock. Their intermediate axis parallels the <u>a</u>-axis in the schist. Both <u>a</u> and <u>b</u> lie in the foliation plane, <u>s</u> (6,p.45;10,p.57). The prominent banding of

PLATE VII



Banded biotite-quartz schist
with wider quartz exudation
bands, thin bands of quartz
mosaic, and dark biotite-rich
bands. Small, light-colored
spots in the biotitic bands
are almandine. West flank,
Jim Hill Mt. (spec. 1-13-9-49).

the schists makes their minute details of often intricate folding very conspicuous.

Garnet, usually less than a quarter inch in diameter, frequently studs the schistose bands (Plate VII).

A microscopic examination of a typical biotite-quartz schist impresses one not only with the distinct banding but also with the high content of quartz (Plate VIII). Quartz usually comprises 70 to 75 per cent of the rock. The wider quartz bands are composed of large, irregular, crystalloblastic grains of quartz, with small amounts of elongate biotite and accessory graphite usually occupying positions of random orientation in the intergranular spaces. Undulatory extinction and the presence of sheared marginal areas which have subsequently recrystallized, plus the inclusion of elongate biotite grains, indicate that these bands have participated in the deformation of the schist. Occasional small anhedral individuals or irregular aggregates of plagioclase occur between the larger quartz grains. This plagioclase varies from Ab_{70} to Ab_{75}. It has the same composition as that occurring in the other two kinds of bands which make up the rock. These quartz bands with their elongate biotite inclusions appear to be due to metamorphic differentiation under conditions of active stress. They may be called exudation bands which lie between zones of intense shearing.

PLATE VIII

(Photomicrograph, crossed nichols) Banded biotite-quartz schist. Above: quartz-rich band with large grains of strained quartz and subordinate plagioclase. Middle: finer-grained mosaic of quartz. Below: biotite-rich band. Southeast flank of Union Peak (spec. B-10).

These thicker quartz bands are in most cases adjacent to the thin, greyish, quartz-rich biotite schist bands which consist of a very fine-grained mosaic of strained, irregularly-shaped, usually equi-dimensional quartz, and subordinate biotite and plagioclase (Plates VIII and XI). The over-all structure is best described as granulose, with elongate biotite and subordinate magnetite, graphite, and garnet oriented to form a well-marked but discontinuous foliation.

The third and last type of band, which is darker and rich in biotite, exhibits pronounced foliation (Plate X). A fine-grained, irregular-shaped mosaic of quartz is associated with large quantities of elongate biotite forming layers of longitudinally-varying extent which are often continuous over considerable distances. The biotite is of a reddish-brown to chocolate-brown color, is extremely pleochroic, and usually contains well-developed pleochroic haloes around tiny zircon nuclei. Graphite is frequently aligned along the cleavage planes of the biotite, and grains and irregular masses of magnetite are common inclusions in the biotite.

Generally the schists show two generations of biotite. The older generation consists of parallel flakes in the plane of schistosity which are usually 5 to 7 times as long as thick. At the apices of microscopic folds the biotite has usually been bent, though recrystallization of folded biotite layers in polygonal arcs also occurs. The first generation of biotite is

PLATE IX

(Photomicrograph, plane polarized light) Contorted biotite-quartz schist. Postkinematic crystallization of biotite both along and across the foliation. Graphite bands, marking the foliation, are included in the biotite. Main peak, Mt. Fernow (spec. 1-3-9-49).

PLATE X

(Photomicrograph, crossed nichols) Mica-quartz schist with synkinematic biotite marking the foliation, and randomly oriented postkinematic biotite (b) and muscovite (m). Almandine (a) at lower left. Summit of Nason Ridge east of Lake Merritt (spec. B-23c).

PLATE XI

(Photomicrograph, crossed nichols)
Almandine porphyroblasts (dark) in biotite-rich layer of banded biotite-quartz schist. West flank, Jim Hill Mt. (spec. 1-13-9-49).

synkinematic, being the result of crystallization contemporaneous with deformation (Plate X).

The second generation of biotite, usually minor in quantity, consists of irregularly-shaped plates, often without appreciable elongation, which either roughly follow the schistosity marked by the synkinematic biotite or grow across the foliation at various angles. This generation represents a period of dying deformation and a static phase of crystallization immediately following it (Plate IX).

Muscovite, present locally in small quantities, displays the same two generations as the biotite. The second generation muscovite usually consists of rather ill-defined and irregularly-bordered grains (Plate X).

To sum up, the typical schist is composed of three distinct types of bands, with quartz and biotite the dominant minerals, and graphite, magnetite, plagioclase, and muscovite present in subordinate quantities. This main type of schist is the basis for quite a number of special varieties which are characterized by the presence of additional constituents, such as one or all of the following minerals: almandine, kyanite, and staurolite.

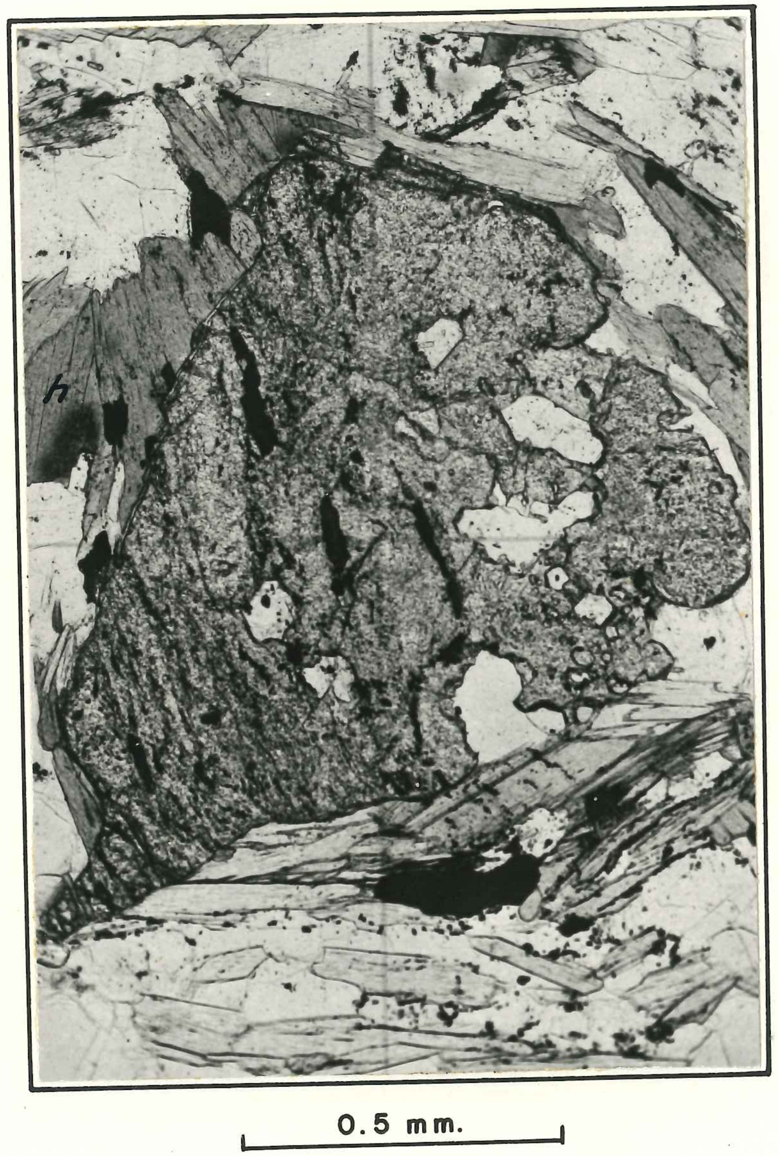
Almandine may or may not occur in rock types of otherwise identical composition (Plate XI). The almandine displays good examples of different times of crystallization with regard to phases of deformation. Some show a well-defined

S-shaped internal s (10,p.57) consisting of graphite and quartz inclusions, indicating rotation during garnet growth. Others exhibit a straight internal s which has been rotated 90° or less, indicating renewed deformation after static garnet growth (Plate XII). In either case the almandine is later than the primary deformation which has formed the s of the schist. The garnet, through crystallization force, has invariably bowed-out the biotite on both sides across the foliation and permitted a random growth of biotite in the "stress shadow areas" resulting from the garnet growth (Plate XII).

Kyanite and staurolite are frequent constituents of the schists and may occur together or separately. Their amount may reach 10 per cent of the rock. Normally confined to the darker, biotite-rich bands of the schist, the kyanite most often forms broad, elongate, tabular plates, the c-axes of the kyanite lying in the plane of schistosity. In many schists, particularly at the axes of folds, the kyanite is bent. Commonly, this kyanite contains an internal s consisting of graphite. In a few cases the kyanite has grown across the plane of foliation (Plate XIII). This phase of kyanite growth is later than deformation and is obviously due to high temperatures continuing under static conditions.

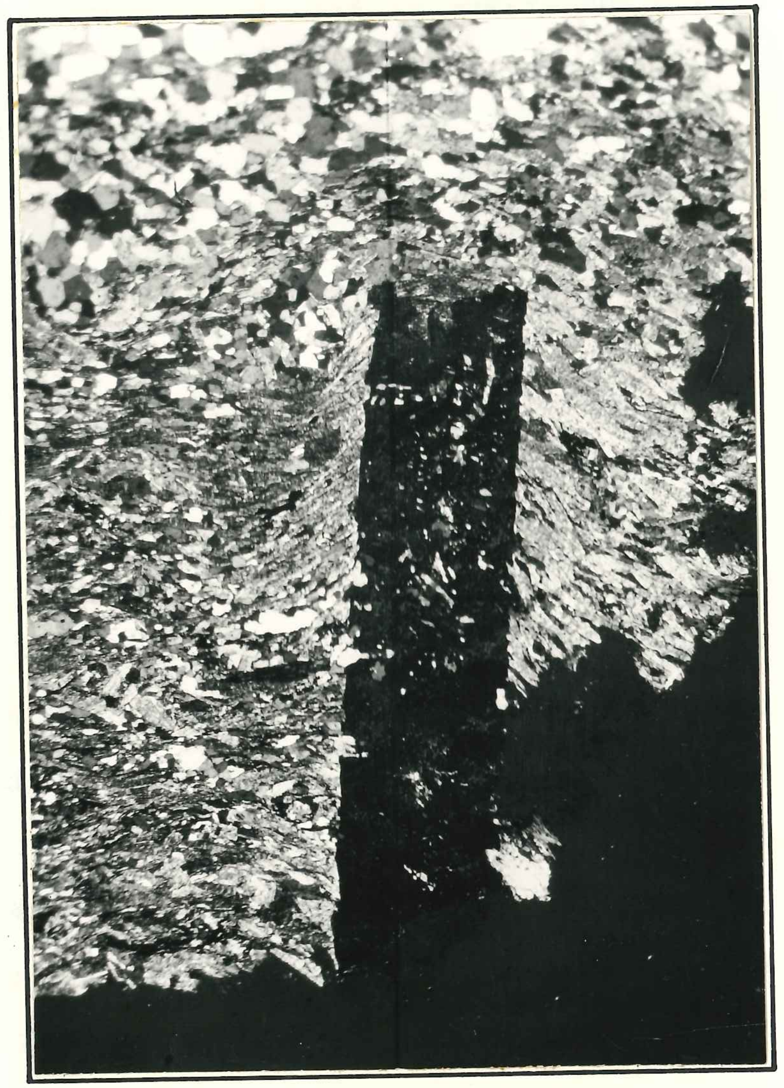
Staurolite occurs either as rounded, irregular grains or, occasionally, in six-sided, idioblastic cross-sections

PLATE XII



(Photomicrograph, plane polarized light) Almandine with an internal s of graphite and magnetite displaying post-crystalline rotation. Plane of foliation of biotite-quartz schist lies from left to right. Randomly oriented biotite has formed in the ? ↔ "stress shadow" areas left and right of the garnet. Biotite plate at upper left contains a dark, pleochroic halo (h) around a small zircon grain. Schilling Creek (spec. 1-15-10-49).

PLATE XIII



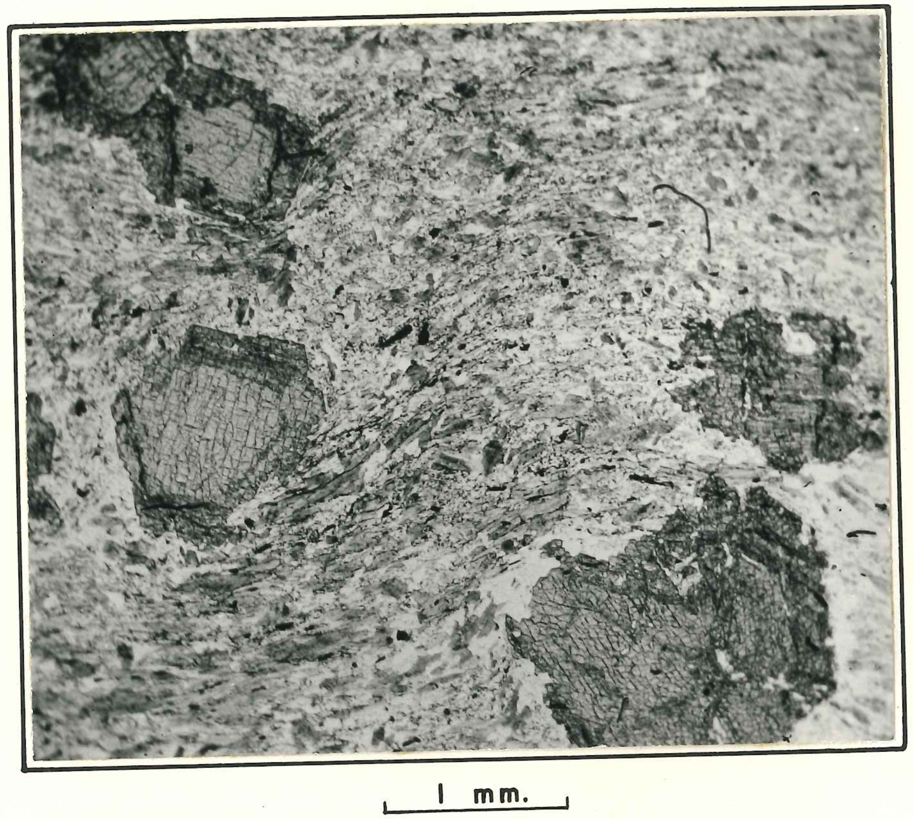
(Photomicrograph, crossed nichols) Postkinematic kyanite idioblast (dark) transecting foliation of biotite-quartz schist. Growing porphyroblast has bent out the foliation of the groundmass. Some recrystallization of biotite, muscovite, and quartz in the groundmass has produced a very slight superimposed hornfelsic texture. South slope of Mt. Howard (spec. C-15d).

which are usually elongated in the plane of foliation. Irregularly-shaped inclusions of quartz and graphite are common. This staurolite is in part synkinematic and is in part postkinematic or static (Plate XIV).

On the southwest flank of Rock Mt. are found very fine-grained, highly carbonaceous biotite-quartz schists which appear to contain large (up to 20 mm in length) porphyroblasts of chiastolite with well-developed graphite crosses. Microscopic examination discloses the fact that these porphyroblasts are not composed of chiastolite but are composed of kyanite and staurolite which are pseudomorphs after chiastolite. It is of interest that in this process the graphite crosses of the chiastolite were inherited without apparent change by the kyanite and staurolite (Plate XV). This apparently indicates that a static growth of chiastolite under temperature conditions typical of the warmer part of the mesozone preceded a phase of dynamic metamorphism during which kyanite and staurolite were produced.

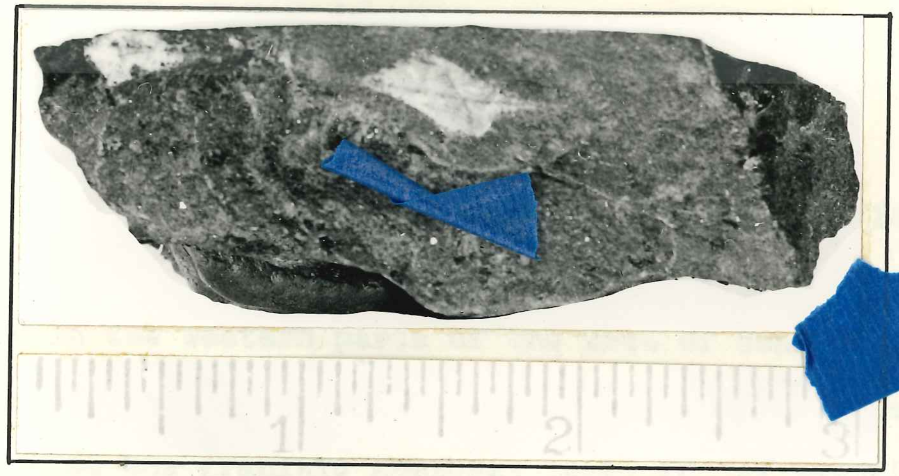
A study of many thin sections has convinced me that the schists of this area cannot be assigned to separate kyanite or staurolite zones. These two zones of Barrow's (1) classical scheme do not apply here. In fact, their validity has been questioned by several petrographers, including H. H. Read and Peter Misch. In the area here described, rocks which contain either kyanite or staurolite, as well as rocks

PLATE XIV



(Photomicrograph, plane polarized light) Idioblasts of staurolite in a staurolite-kyanite-biotite-quartz schist. Staurolite has bent out foliation of mica schist matrix. Southeast flank, Rock Mt. (spec. B-12a).

PLATE XV



Kyanite and staurolite forming pseudomorphs after chiastolite (light-colored areas) in a fine-grained graphite-staurolite-kyanite-biotite-quartz schist. Southeast flank, Rock Mt. (spec. B-12b).

containing both, sometimes in oriented intergrowth, are closely associated and irregularly distributed, and no zonal pattern whatsoever is indicated.

In view of what has been written above, and inasmuch as the kyanite and staurolite are clearly contemporaneous in many rocks of this area, the quartz-biotite schists are assigned to the kyanite-staurolite zone. This zone corresponds to the hotter part of the medium grade or mesozone (Grubenmann, 5) of regional metamorphism.

Hornblende-Bearing Schists

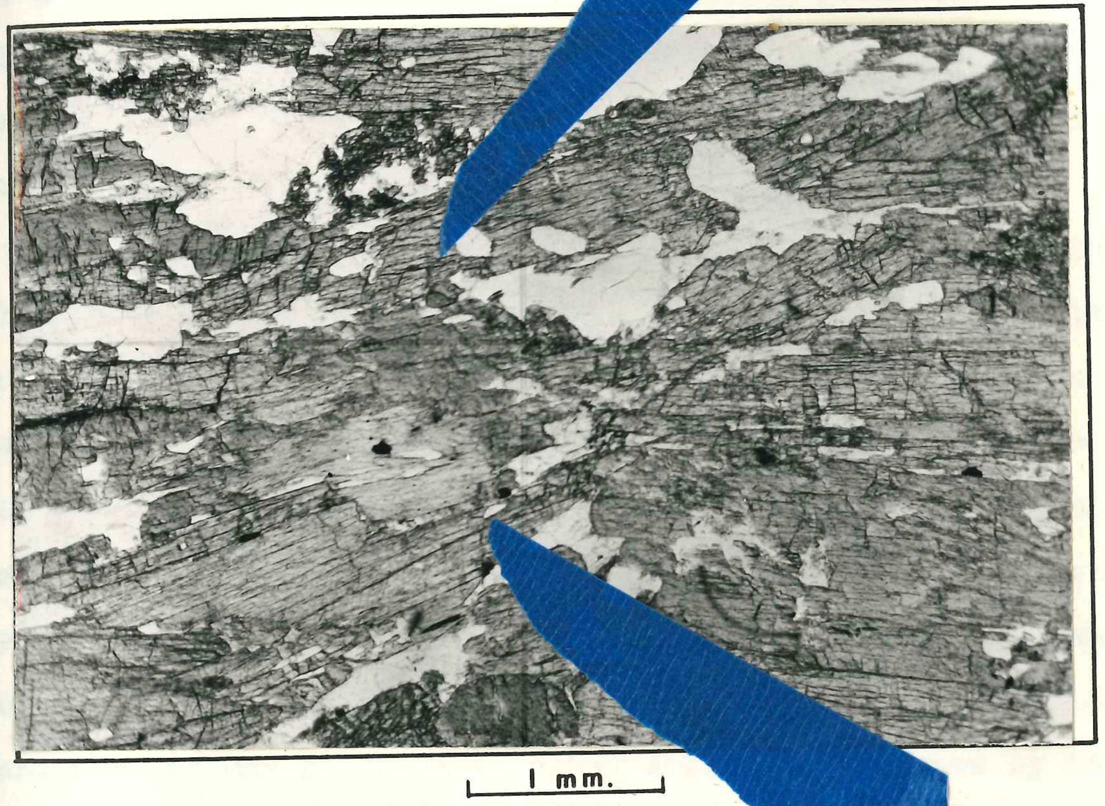
Subordinate hornblende-bearing schists are intercalated in the dominant biotite-quartz schists. They occur most frequently in the western parts of the area of schists, particularly near the town of Berne. There are also occurrences adjacent to the granitic gneisses found in the vicinity of Merritt. Similar hornblende-bearing schists have been described by Page (7) in the vicinity of Chiwaukum Creek. Hornfelsized remnants of these hornblende-bearing schists occur in the migmatite zones at the contacts of the schists with the granitic rocks to the west and the granitic gneisses to the east. The hornblende-bearing schists occupy zones having a maximum-observed width across the strike of 300 yards.

Most of the hornblende-bearing schists are rich in biotite and are often megascopically indistinguishable from the ordinary biotite-quartz schists. The hornblende is commonly too fine-grained to be megascopically visible. Both the major schist types are usually banded, but the bands in the hornblende-bearing schists are usually thinner and less conspicuous. The wide quartz-exudation bands so typical of the biotite-quartz schists are in most cases absent. A dark, greenish hue occasionally helps one to recognize the hornblende-bearing schists in the field.

Microscopic examination of the hornblende-bearing schists shows that they are highly variable. No one particular occurrence can be designated as typical. The only common characteristics of these rocks are their schistosity and the presence as a major constituent of hornblende.

The amount of hornblende varies from extreme values of about 5 per cent to as much as 90 per cent of the rock but is commonly between 20 and 40 per cent. Other minerals in these rocks are biotite, quartz, plagioclase, and accessories. The hornblende is usually of a pale green color, being pleochroic from almost colorless to olive-green. The optical properties indicate an amphibole intermediate between actinolite and common green hornblende. Therefore, this amphibole will be referred to as actinolitic hornblende. In a few cases the amphibole is common green hornblende. This applies to all those rock varieties with an unusually high amphibole content. However, such true amphibolites are rare (Plate XVI).

PLATE XVI



(Photomicrograph, plane polarized light) [illegible]ibolite: common green hornblende in subparallel arrangement; subordinate plagioclase and quartz. Divide between Butcher and Kahler Creeks (spec. B-36).

The hornblende mostly occurs in sub-equidimensional grains in an imperfect subparallel arrangement. Much of it has been recrystallized after the end of deformation. Prisms of synkinematic hornblende do, however, occur, and these accentuate the schistosity. In the hornfelsized zones adjacent to granitic rocks, recrystallization of the hornblende has almost destroyed the original schistosity as far as a preferred orientation of minerals is concerned. However, the over-all banding has survived.

Biotite is usually present and it may exceed the hornblende in quantity. Usually the biotite and the hornblende are intimately mingled in the fabric of the rock. Only in a few localities has an alternation of biotite- and hornblende-rich layers been observed. As in the case of the hornblende, two generations of biotite are evident. The first generation is synkinematic; the second is postkinematic and is dominant. Much of the biotite has formed from the actinolitic hornblende. This biotite may follow the relict schistosity marked by the synkinematic hornblende, or it may grow across the foliation at various angles. Wherever biotitization has occurred, irregular aggregates of magnetite become common. In a few cases biotitization has almost eliminated the hornblende.

Quartz is usually present and varies in quantity from an accessory mineral to a major component. It may be almost lacking in those few amphibolites which are rich in common green hornblende. The amount of quartz tends to be inversely proportional to the amount of hornblende.

Plagioclase usually occurs in minor quantities. It is present in all quartz-bearing varieties, and in those amphibolites which contain common green hornblende the plagioclase is far more prevalent than the quartz. In the hornfelsized hornblende-bearing schists found in migmatitic zones there has evidently been sufficient introduction of sodium and silica to cause the appearance of plagioclase at the expense of quartz. The plagioclase is more calcic than that of the biotite-quartz schists, and it varies in composition from Ab$_{60}$ to Ab$_{65}$.

Accessory almandine may be present but is never as prevalent as in the biotite-quartz schists.

Regional retrogressive alteration has strongly affected many of these hornblende-bearing schists. The biotite is often completely altered to chlorite. The pleochroic haloes around zircon nuclei characteristic of the biotite are inherited by this chlorite. Epidote, zoisite, and clinozoisite are frequent alteration products of plagioclase and hornblende. Sericite has also formed from plagioclase, often to such an extent that the type of plagioclase is nondeterminable. Some bent feldspars are evidences of some deformation during this retrogressive phase.

Genetic Evaluation

The petrographic features of the major types of schist have been described above. A genetic evaluation of these features appears to indicate the following sequence of events.

1. A thick sequence of sediments formed the material from which the schists were made. The bulk of these sediments were argillites rich in silica and alumina. The alumina excess of these rocks, as demonstrated by the development of kyanite, staurolite, and local chiastolite, is evidence that the original rocks were argillaceous sediments. The hornblende-bearing schists and the subordinate amphibolites were derived either from dolomitic argillites or from tuffs of predominantly intermediate, and subordinately basic, composition.

2. Intense isoclinal folding with concomitant synkinematic regional metamorphism of medium grade occurred, and a schistose structure was produced. As temperature rose to that of the kyanite zone, kyanite, staurolite, and almandine developed. These minerals generally occur in porphyroblasts postdating the main phase of deformation during which the schistosity was produced, but recurrent deformation is indicated by rotated almandine, and kyanite with a pronounced internal s. Some minor folding, frequently deforming the foliation planes, also belongs in a postschistosity phase of deformation (Plates IX and X).

3. Succeeding the synkinematic metamorphism and continuous with it, a static phase of crystallization occurred. Mesozonal temperatures persisted, and some kyanite, biotite, and muscovite grew across the schistosity with random orientation (Plates IX, X and XIII).

4. As temperatures decreased at the end of metamorphism, retrogressive minerals such as muscovite, sericite, chlorite, and epidote formed. Some of the sericite and chlorite present, however, is due to recent weathering.

5. The last major event was tectonic and produced a large, open, plunging syncline (cf., page 14) superimposed on the isoclinal folding of the schists.

Gneisses

Distribution and Associations

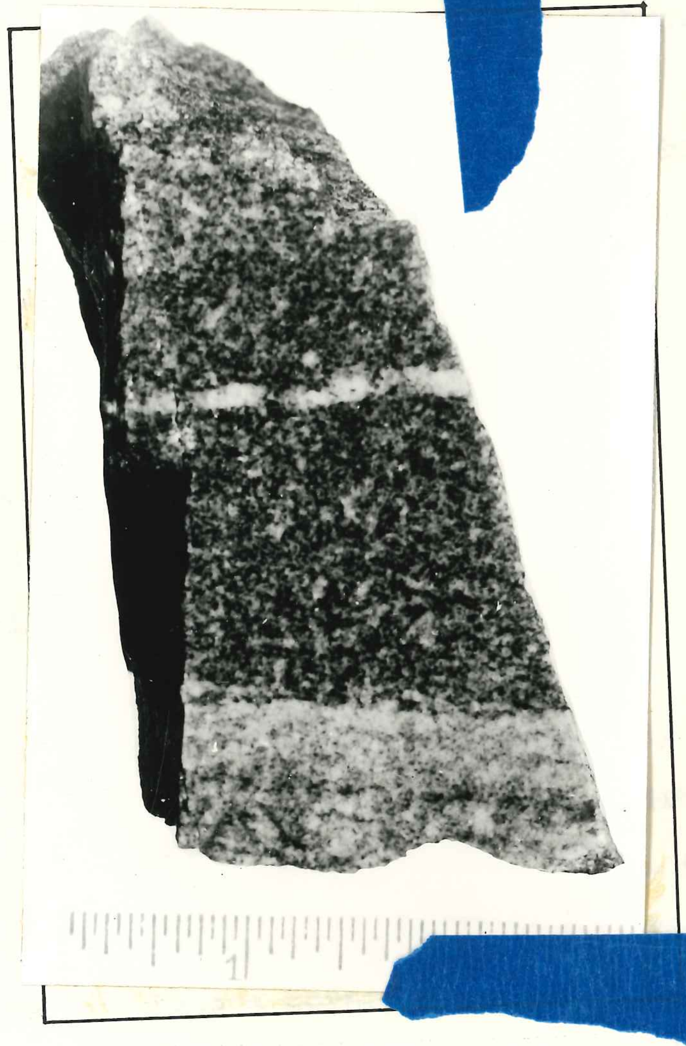
About one mile west of Merritt (Plate A) the schists grade across their strike into a migmatitic zone in which gneiss and schist occur in varying proportions. This migmatite zone continues to a point just east of Merritt where a transition to an area of dominant gneiss occurs. These gneisses then continue eastward for approximately four miles to a fault contact with the supposedly Paleocene continental sediments of the Swauk formation (2,11,19,20). This fault trends north-south and lies about a quarter mile east of Butcher Creek. It is accompanied by a brecciated zone approximately 200 yards in width.

The gneisses, however, are not confined to a zone only four miles in width in other parts of this general area. During a reconnaissance trip to the northern shore of Lake Wenatchee similar gneiss was found to occur on the flanks of Dirty Face Peak (see Chiwaukum quadrangle, 17, a). Willis (20) has shown that similar gneisses extend farther to the east. Certain types of gneisses found in the Nason Ridge area are identical with rocks occurring in the Entiat Mountains east of the graben which contains Lake Wenatchee and the Swauk sediments. Waters (18) has found "biotite gneisses," that appear to be similar, grading into the granodioritic gneisses on the borders of the Chelan batholith.

Petrology and Structure

The gneisses of the Nason Ridge area are fine to medium-grained and approach a granitic composition. However, they are highly variable in texture and, to a somewhat lesser extent, in composition. In the migmatitic zone west of Merritt there occur sheets of leucocratic gneisses intercalated in the darker schists, forming a lit-par-lit structure (Plate XVII). Layers of both rocks vary in thickness from an inch to an exceptional maximum of six feet, the average being about six inches. The foliation of schist and gneiss is parallel.

PLATE XVII



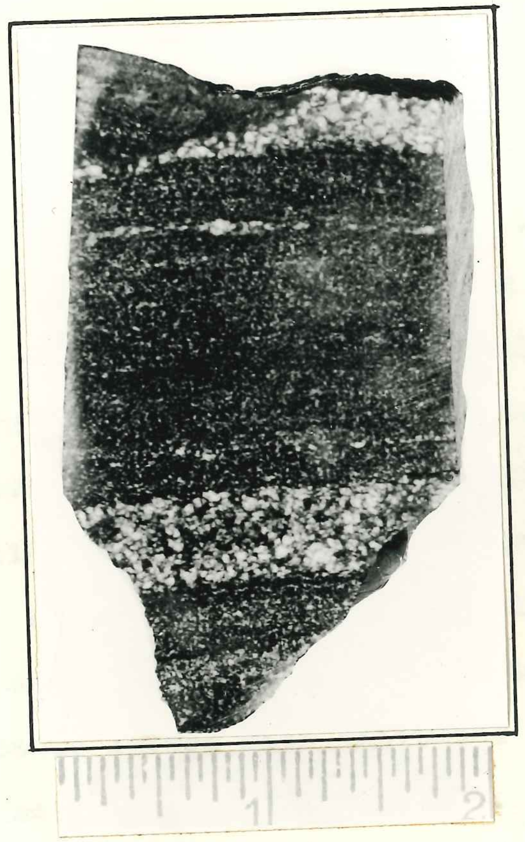
Banded gneiss. Fine-grained highly felspathic layers and medium-grained hornfelsic schist material. One-quarter mile west of Merritt (spec. 7b-25-3-50).

The gneissic layers found in this lit-par-lit structure are composed of a fine- to medium-grained rock with good foliation. Feldspar and quartz are the dominant constituents. Subordinate muscovite and/or biotite, in parallel arrangement, define the foliation.

These gneissic layers grade into the schists. Usually the schists are biotite-quartz schists, but hornblende schists are also found. Most of the schistose layers are hornfelsized to some degree, but the quartz-rich bands and boudins so characteristic of the biotite-quartz schists are usually still in evidence. Felspathization has formed thin bands, rich in feldspar, along the planes of schistosity (Plate XVIII).

Within the migmatite zone west of Merritt, and especially at the railway overpass near the confluence of Whitepine and Nason Creeks, there occurs a second variety of gneiss. It consists of all possible gradations between hornblende schists and fine- to medium-grained granitic gneisses, some of which are almost structureless. The schists have been considerably recrystallized and have a hornfelsic appearance. Along the planes of relict schistosity of these hornfelsized schists augen and lenticular aggregates of feldspar occur (Plate XVIII). These hornfelsic schists grade into more gneissic rocks containing skialiths (Goodspeed, 4)--shadowy relics of incompletely transformed schist. The relict schistosity present in these skialiths is parallel to that of both the

PLATE XVIII



Banded gneiss. Granitoid bands parallel the relict foliation of a hornfelsized and felspathized hornblende-quartz schist. One-quarter mile west of Alpine Lookout, Nason Ridge (spec. B-29a).

enclosing gneiss and the adjacent schist. The skialith-bearing gneiss grades into gneisses free of relict inclusions. It is important to emphasize the parallelism of the foliation in schists, skialiths, and gneisses.

To the east the migmatite zone of Merritt is succeeded by a zone of dominant gneiss. This gneiss is quartz dioritic in composition. The layers of schist found in the lit-par-lit structures near Merritt are lacking. But narrow, dark, micaceous layers, up to one inch in thickness, remain as relics of the schist bands (Plate XX, A). The gneiss often becomes coarser-grained, and the foliation less well-defined (Plate XX, B). Feldspar becomes the major constituent, with quartz minor, and muscovite and biotite mark the foliation. In a few places these gneisses grade into almost directionless granitic rocks. However, even in these relatively directionless rocks there occur occasional very thin (one-quarter inch maximum thickness) micaceous layers with attitudes still parallel to those of the adjacent, more clearly-foliated rocks.

All gradations between schist and gneiss, and gneiss and structureless granitic rocks, may be observed in this area.

Much of the relatively structureless granitic rock of this gneissic area is fine-grained and occurs in steep-sided, irregularly-shaped bodies which transect the gneissic structures. Up to 40 feet in width, these bodies have gradational borders with the gneisses. The rock of these cross-cutting enclosing gneiss and the adjacent schist. The skialith-bearing gneiss grades into gneisses free of relict inclusions. It is important to emphasize the parallelism of the foliation in schists, skialiths, and gneisses.

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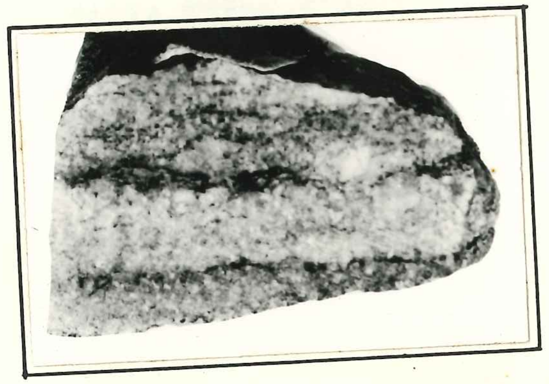
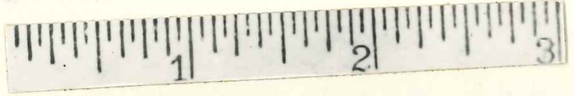
PLATE XIX

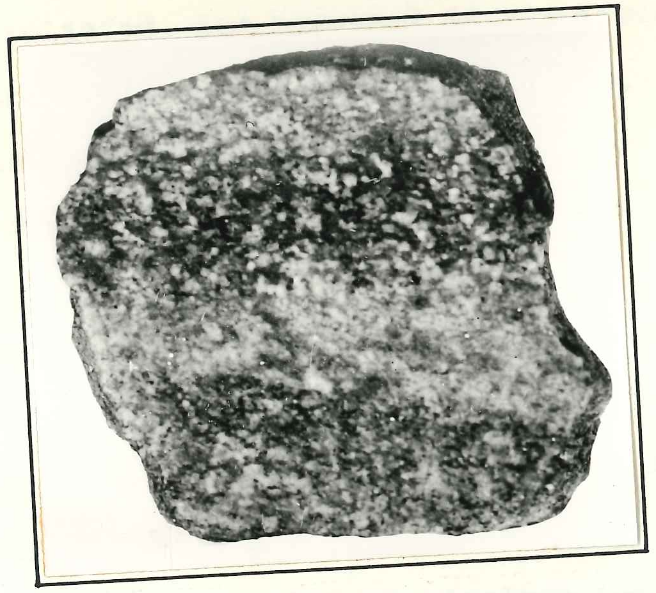
Banded gneiss. Felspathization along planes of relict foliation in a hornblende-quartz schist. Later, cross-cutting, fracture-controlled replacement veins contain microcline, plagioclase, and quartz. South flank of Mt. Howard (spec. C-15c).

PLATE XX



A. Banded gneiss. Mafic minerals mark the relict foliation. One-quarter mile west of Alpine Lookout, Nason Ridge (spec. B-29).





B. Medium-grained banded quartz dioritic gneiss. Foliation marked by alternations of lighter and darker bands varying in mafic mineral content. Summit of Nason Ridge, north of Lake Merritt (spec. B-25).

bodies consists chiefly of feldspar, with some quartz and very few dark minerals. Often, however, relics of gneiss and, occasionally, of schist, occur within these granitic zones. Usually, but not always, such inclusions have a relict schistosity which is parallel to that of adjacent gneissic or schistose rocks.

A microscopic examination of the gneisses shows considerable compositional and textural variability, especially in the migmatitic areas at contacts of the schist and gneiss. However, most of the gneiss forming the light-colored layers in the banded rocks west of Merritt is essentially of the same type as that of most of the rock composing the gneissic area east of Merritt. This common type of gneiss is usually fine-grained, well-foliated, and composed of plagioclase, quartz, muscovite, with subordinate biotite, hornblende, potash feldspar, magnetite, almandine, zircon, and apatite, and retrogressive clinozoisite, epidote, muscovite, sericite, and chlorite.

Plagioclase is the most abundant mineral. It usually forms at least half and occasionally as much as 75 per cent of the rock. The plagioclase occurs as anhedral, irregularly-shaped, crenulated crystals, with a tendency to be elongated in the plane of foliation. The plagioclase individuals interlock, one with another, and with other minerals, in an intricate fashion. The average size of the plagioclase is about

2 mm, but some porphyroblasts reach twice this size. Albite twinning is common, and Carlsbad and pericline twins also occur. Composite twinning is common, and involved zoning is occasionally present.

The larger plagioclase porphyroblasts are filled with inclusions of quartz, muscovite, and often irregular grains of secondary clinozoisite and epidote (Plate XXI). Usually the plagioclase is bent, sometimes in an undulating fashion.

The usual composition of the plagioclase varies from Ab$_{65}$ to Ab$_{75}$. Most is about Ab$_{70}$. However, where hornblende is the main mafic mineral the plagioclase is more calcic, averaging about Ab$_{60}$ (Plate XXII, A and B). A few of the zoned plagioclases show more calcic cores and more sodic rims.

Quartz, in anhedral crystals, may form up to 25 per cent of the rock. The average amount is about 15 per cent. This quartz is strained and displays undulatory extinction. The quartz is intimately intergrown with the plagioclase, and in many cases it is completely enclosed within the plagioclase crystals (Plate XXI). Myrmekitic growth of quartz and feldspar is common.

The most common mica present is muscovite. Two generations are recognizable. The first generation is clear, elongated in the plane of foliation and has ragged terminations. This earlier muscovite commonly has parallel orientation and gives the rock a well-marked, though discontinuous,

PLATE XXI

(Photomicrograph, crossed nichols)
Oligoclase porphyroblast (upper left) containing inclusions of quartz, biotite, and muscovite. Deformed plagioclase (lower right). Quartz diorite gneiss. Lake Merritt (spec. B-24).

PLATE XXII

(Photomicrographs: A, plane polarized light; B, crossed nichols) Felspathized amphibolite. Andesine almost equals common green hornblende. Quartz very minor. Foliation disturbed by partial recrystallization of hornblende. Summit, Nason Ridge, east of Lake Merritt (spec. B-15).

foliation. Occasionally the muscovite can be seen to have formed from the alteration of biotite. Much of this muscovite is presumed to have been derived from biotite, inasmuch as remnants of schist within the bands of gneiss, as well as adjacent bands of schist, are rich in biotite. In addition to this earlier muscovite, some large, irregularly-shaped plates of muscovite grow across the foliation. This later muscovite is usually turbid in appearance and has ill-defined margins. Some of this later muscovite can be seen altered from plagioclase.

Clinozoisite, epidote, and occasional zoisite may form as much as 10 per cent of the rock. They occur as irregular grains in the plagioclase and also in the intergranular spaces of the rock. Occasionally these minerals can be seen closely associated with biotite, in which case they are presumed to have formed as a result of biotitization of earlier hornblende. This interpretation is usually supported by the presence of hornblende in adjacent layers of schist and occasional, partially-biotitized, remnants of hornblende preserved in the gneiss. In other cases these minerals are an alteration product of the plagioclase, and thus may be considered as indicative of a retrogressive phase of metamorphism.

Almandine, with inclusions of quartz, biotite, and occasional clinozoisite, is an accessory.

In the migmatitic areas, especially west of Merritt, this gneiss is transitional with the schists. Within a few inches the gneiss grades into biotite-quartz schists or hornblende-bearing schists. The schist bands which are immediately adjacent to the gneiss bands have undergone a phase of static recrystallization. As a result, they have acquired a superimposed hornfelsic texture and have partially lost their schistosity (Plates XVII and XVIII). The biotite and muscovite, and the hornblende, of these hornfelsized schists have frequently grown across the relict schistosity. Small porphyroblasts of plagioclase of the same composition as in the gneiss form thin bands in the schists parallel to their schistosity. As the gneiss is approached, these bands become wider and the porphyroblasts larger.

A comparison of adjoining layers of schist and gneiss often shows the two do not differ very radically in texture or mineral composition. Whereas quartz is usually the dominant constituent in the schists, plagioclase assumes that position in the gneisses. Most of the biotite of the schists becomes muscovite in the gneisses, and the total amount of mica is reduced. Where hornblende was a major constituent of the schist, biotite, muscovite, clinozoisite, and epidote are present in the adjoining gneiss. Aside from these main differences, the other mineral constituents of the gneisses and schists are identical in type and, usually, in quantity. For example, the almandine so prevalent in many of the schists is inherited by the gneiss.

In the gneiss described above, and also in many of its varieties, potash feldspar may be found. Usually this is microcline. Almost invariably the microcline is found in porphyroblasts along what appear to be rather narrow zones transecting the gneissic structure. These microcline porphyroblasts average 2 mm, but exceptionally attain 7 or 8 mm in size. The microcline is normally associated with a very noticeable vermicular growth of quartz and plagioclase. Several occurrences show the plagioclase being engulfed by microcline.

Genetic Interpretation

Both structural field evidence and microscopic study of the gneisses near Merritt indicate that they have been derived from the schists through processes of syn- and post-kinematic metasomatism.

In the field it is observed that the contacts between schists and gneisses are invariably gradational. In addition, the foliation of adjacent gneisses and schists is usually parallel; this equally applies where thin and long lenticular bands of schist are completely enclosed in gneiss, as well as where smaller relics of schist occur in the gneiss.

The petrographic features of the gneisses and their contacts with the schists have been described above. A genetic evaluation of these features indicates the following probable sequence of events.

1. During, and after, the orogenic metamorphism which isochemically formed the schists, an introduction of sodium and silica occurred in the areas now occupied by gneisses. This assumption is necessary to explain the presence of plagioclase as the dominant constituent of the gneisses, in contrast to the plagioclase-poor schists. At the same time the hornblende of the hornblende-bearing varieties of schist was biotitized, thus indicating an introduction of potassium in addition to sodium and silica. At a later stage biotite was extensively, in some cases even completely, converted to muscovite. The biotitization of hornblende released mainly calcium, whereas the transformation of biotite into muscovite set free magnesium and iron. Apart from these mineral transformations, the total amount of mica also decreased during the felspathization responsbile for the formation of the gneisses. This led to a further release of iron and magnesium, as well as aluminum which later was utilized in the production of metasomatic feldspar. No kyanite or staurolite are preserved in the gneisses.

The genesis of the plagioclase may be outlined as follows: The aluminum silicates present in the schists;

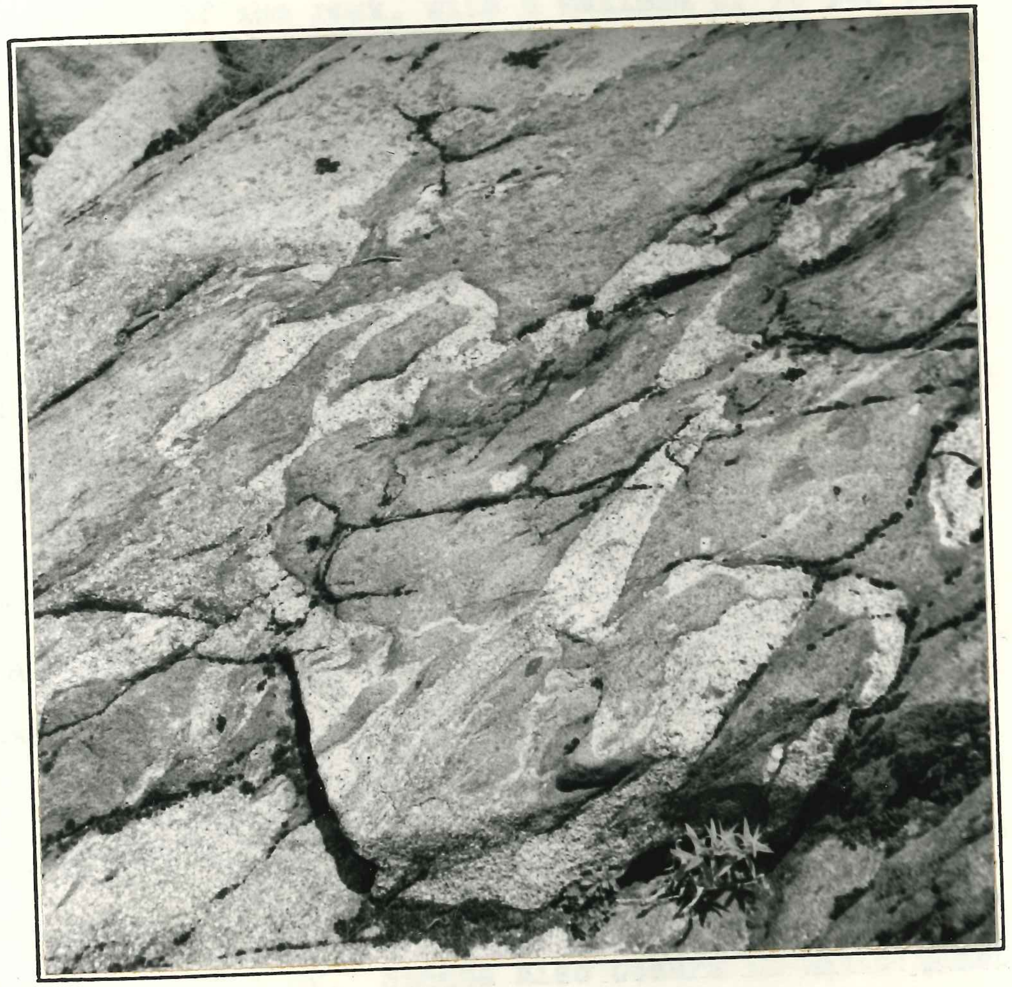
further aluminum set free by the breaking-up of mica; some of the quartz of the schists; and the calcium set free as a result of biotitization of hornblende: all combined with the metasomatically-introduced sodium and silica (cf., above) to form the plagioclase which is so dominant in the gneisses. This plagioclase varies from oligoclase to andesine (cf., page 46). Where hornblende was a major constituent of the schists, the relatively large amount of calcium released by biotitization of the hornblende tended to make a comparatively more calcic plagioclase approximating Ab_{60} in composition. Where biotite was the dominant mafic in the schist, and hornblende was either minor or absent, the plagioclase of the resultant gneisses was more sodic and approximated Ab_{75} in composition. This variability can definitely be correlated with the original composition of adjacent schists.

2. The processes described in (1) continued after the end of deformation. High temperatures and sodium and silica introduction evidently continued, for large porphyroblasts of plagioclase, with haphazard orientation, developed during this postkinematic or static phase of felspathization, both in the gneisses and the adjacent schists. Transverse grains of biotite, muscovite, and hornblende grew across the foliation of the schists, and to a certain extent a hornfelsic texture was superimposed on the schistosity. Hornfelsizing is especially marked where schists are adjacent to gneisses (Plate XVII).

3. Following the making of these gneisses, widespread fracturing appears to have occurred. A system of cross-cutting fractures was formed along which dike-like and some more irregular bodies of predominantly fine-grained granitoid rock were produced, both in the gneisses and the schists. These transecting bodies of granitoid rocks are usually considerably longer than wide and most usually have a dike-like over-all shape. Often one contact is rather well-defined, suggesting a pre-granitic cross-cutting fracture as a marginal control. The other contact of such bodies is generally irregular in detail and gradational with the country rock. In some of these granitoid bodies haphazardly-arranged inclusions of schist and gneiss are found, suggesting a fault breccia which has been invaded by the granitic materials (Plate XXIII). In other cases the inclusions have attitudes parallel to those of the surrounding schists or gneiss and obviously have not been displaced. Flow structures parallel to the longer axes of these granitoid bodies are in most cases absent, and not infrequently the parallel structure of the enclosing gneiss or schist can be traced across the dike-like bodies as a relict structure.

These cross-cutting dike-like bodies commonly consist of a fine-grained, "salt and pepper"-like granitoid rock. Microscopic examination shows that this granitoid material grades into the country rock at one or both contacts. The

PLATE XXIII



Migmatite zone. Brecciated biotite-hornblende-quartz schists partially replaced by granitic materials. Inclusions of schist material vary from skialiths to hornfelsized schists. Southeast spur of Union Peak.

average size of the mineral components is 0.2 to 0.5 mm, though occasional pegmatitic examples may have crystals as large as 20 mm in size. Plagioclase, varying from Ab_{65} to Ab_{75} in composition, is the dominant mineral, and it averages 60 per cent of the rock, with a maximum of 70 per cent. The larger plagioclase crystals, usually around 0.5 mm in size, commonly approximate Ab_{65} in composition, with the smaller, later crystals being more sodic. In all cases the plagioclase is anhedral and shows irregular margins characteristic of crystalloblastic growth. The smaller, more sodic plagioclase grains grow at the expense of the larger, more calcic plagioclase, as well as of the quartz and biotite.

Quartz averages 15 per cent of the rock and forms anhedra varying in size from large, irregular grains to smaller, more rounded crystals formed in the intergranular spaces.

Biotite is usually the only important mafic constituent and is haphazardly-arranged in irregular plates that usually possess ragged, fuzzy terminations and vary in size from 0.1 to 0.5 mm. Sphene also occurs in minor quantities.

These cross-cutting granitic bodies closely approach a quartz dioritic rock in composition.

An examination of many of these dike-like bodies leads to the conclusion that the majority have formed by replacement in situ. Occasionally, however, flow structures have developed parallel to the dike walls, and the dike is interpreted as being a mobilized migmatite which has become locally intrusive.

In addition to the minerals described above, occasional porphyroblasts of microcline are found which encroach upon and engulf plagioclase, quartz, and the other constituents of these dike-like bodies (cf., page 51). These microcline porphyroblasts always occur in narrow, often microscopic, vein-like elongate zones transecting the pre-existing dike and the adjacent gneisses. Invariably this microcline is associated with a vermicular growth of quartz and plagioclase. The presence of this potash feldspar suggests a potassium introduction during a postkinematic phase of crystallization.

4. The last event is the formation of epidote and sericite from the plagioclase, and chlorite from the biotite of the gneisses. Apparently the low temperature minerals were formed during a phase of retrogression at the end of metamorphism when temperatures were falling, but part of the sericite and chlorite is due to recent weathering.

Granitic Rocks

Distribution

A varied group of granitic rocks underlies a large area west of the schists. They compose the Stevens Pass region proper and the peaks lying north and south of the Pass along the Cascade Crest. The area of these granitic rocks

PLATE XXIV

Migmatite zone. Relict foliation preserved in granitoid rocks by layers differing in content of mafic minerals. Later cross-cutting replacement veins and dikes contain microcline, plagioclase, and quartz. Lake Valhalla.

in dike-like, irregular bodies up to 50 feet in width. Such bodies contain numerous irregularly-shaped, haphazardly-oriented fragments of schist material which appear to indicate that brecciation of the schists has facilitated the emplacement of the granitic materials (Plate XXV). Excellent examples of this type of contact can readily be seen along the highway in the road cuts above and below the confluence of Mill and Nason Creeks.

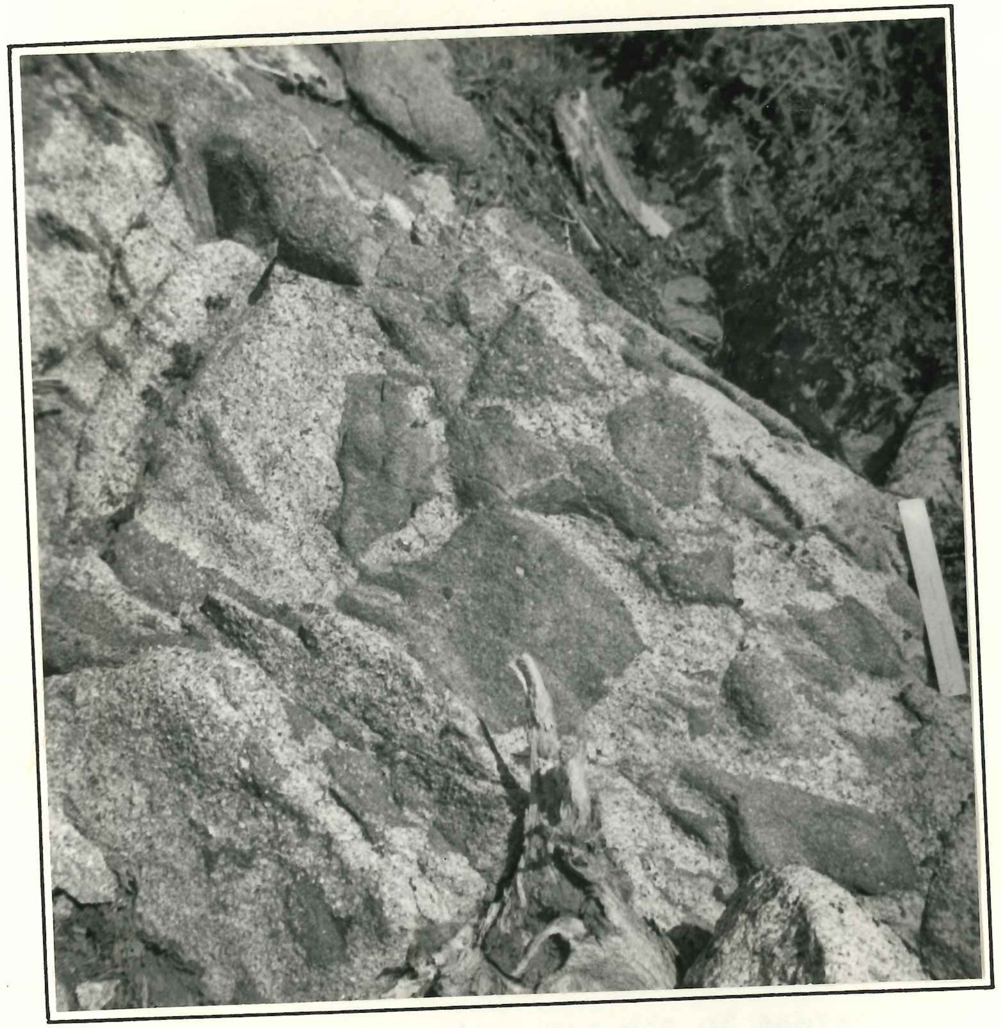
The second type of contact is restricted to the ridge just south of the main summit of Mt. Fernow (Plate A). This contact is moderately to absolutely sharp and discordant (Plate XXVI). Here, also, the granitic rocks adjacent to the schists are filled with inclusions of the schists in varying stages of transformation, and the marginal several hundred yards of the granitic rocks can be considered a migmatite zone.

The rocks of the main granitic body will be described first, and those of their comparatively narrow migmatitic border zones later.

Description of the Main Granitic Body

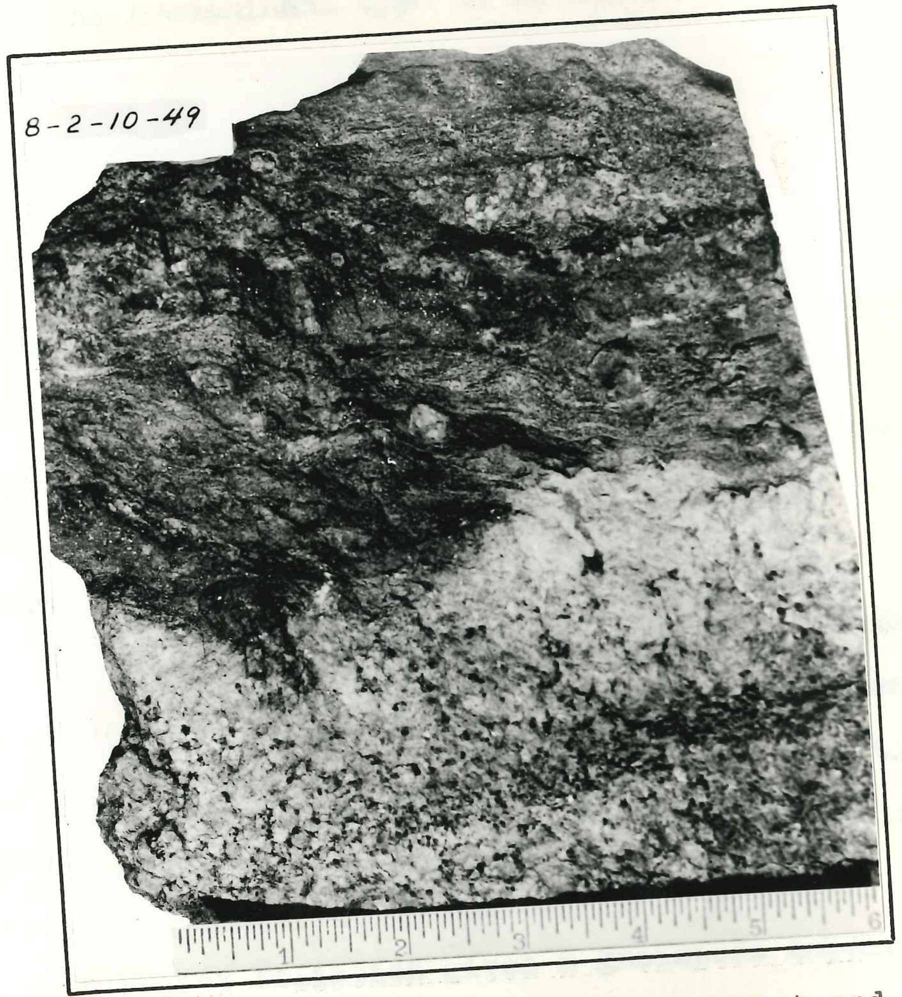
The granitic rocks vary considerably in appearance and, to a lesser extent, in composition. Some are dark, bluish-grey, medium-grained, dioritic-like rocks dominantly composed of plagioclase, hornblende, and biotite. These

PLATE XXV



Migmatite zone. Partial granitization of brecciated schists. Inclusions of schist material display varying degrees of felspathization and transformation. Southeast spur of Union Peak.

PLATE XXVI



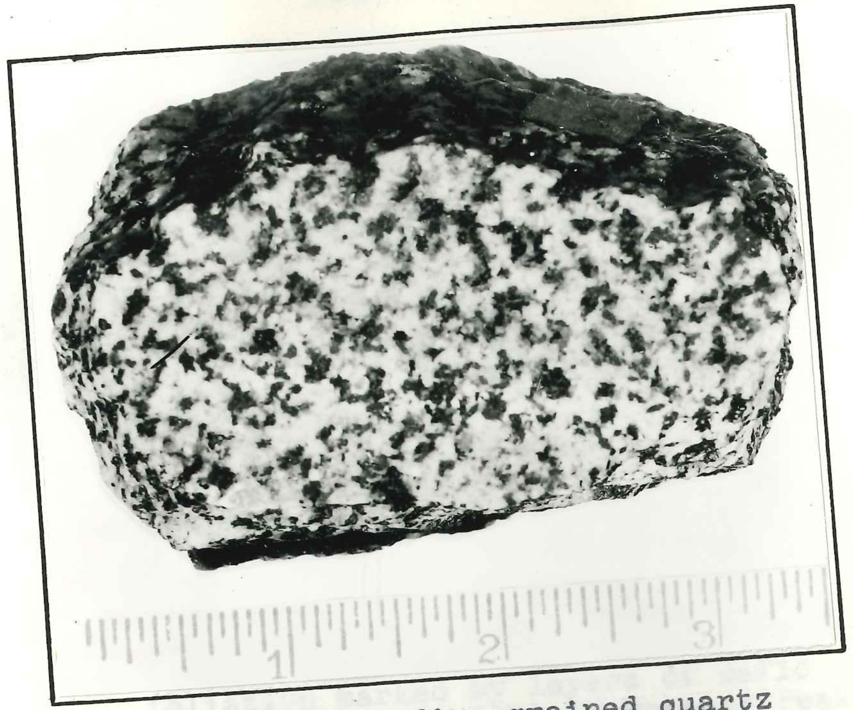
Sharp and discordant contact of schist and granitoid rock. Schists with a slight superimposed hornfelsic texture. South ridge of Mt. Fernow.

dioritic rocks are usually restricted to the relatively narrow migmatitic zones on the borders of the main granitic body. Other rocks, quantitatively unimportant, are very light in color, with plagioclase and quartz dominant, and few mafics present. The predominant type is an intermediate, leucocratic rock which is medium-grained and composed chiefly of plagioclase and quartz with biotite and hornblende in small, unevenly-distributed patches (Plate XXVII, A).

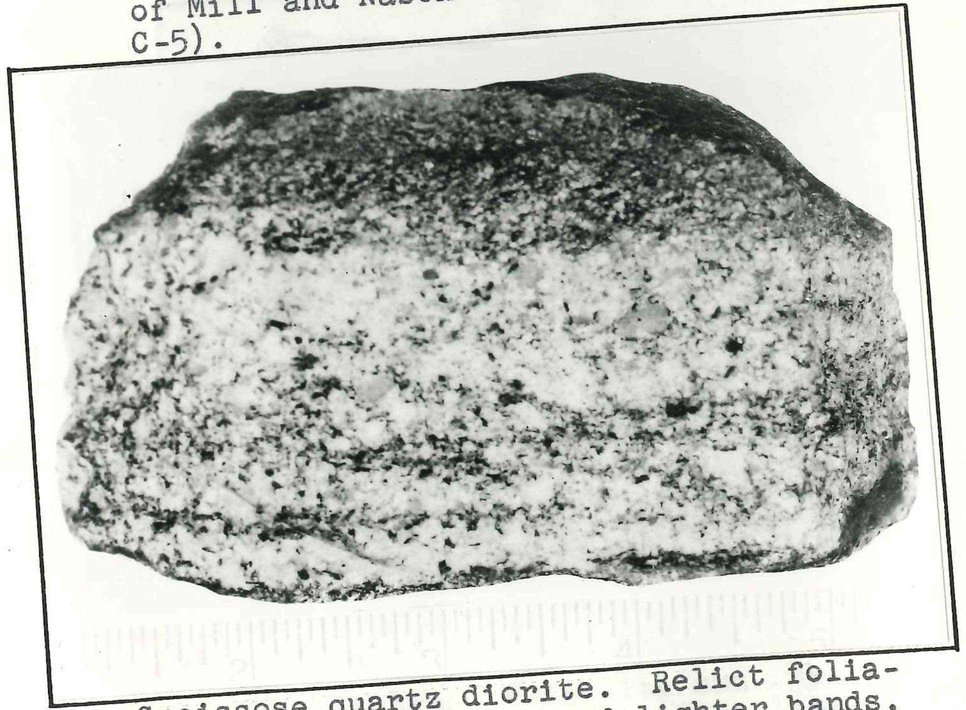
Structures and Inclusions. These dominant granitic rocks have apparently been considered as structureless and homogeneous by Smith (13,p.157). Inasmuch as most of them lack any preferred orientation of the mineral components, this is true. However, in many other ways they are far from being structureless and homogeneous.

Relict foliation is often found in these granitic rocks. Usually it is not associated with a preferred orientation of minerals but is displayed by varying proportions of dark and light minerals in alternating layers and elongated lenticles (Plate XXVII, B). There are numerous small areas where such relict foliation gives a gneissose appearance to the granitic rocks (Plates XXVII, B, and XXVIII, A and B). In the area southwest of Lake Valhalla, on the southeast spur of Union Peak above Smith Brook, and on Barrier Peak there are extensive northwest-southeast elongate areas, ranging from several hundred yards to over a mile in length, in which this

PLATE XXVII



A. Leucocratic, medium-grained quartz dioritic rock. Patchy arrangement of mafic minerals. Near confluence of Mill and Nason Creeks (spec. C-5).



B. Gneissose quartz diorite. Relict foliation marked by darker and lighter bands. Lake Valhalla (spec. B-2).

PLATE XXVIII

A. Quartz diorite. Variation between a directionless rock and one with relict foliation marked by layers of mafic minerals. East ridge of Barrier Peak (spec. 1-16-9-49).

B. Quartz diorite gneiss. Relict foliation marked by subparallel orientation of biotite and hornblende. Summit of Barrier Peak (spec. 2-9-9-49).

relict foliation prevails (Plate B). In such areas the rock can be called a gneissose granitic rock. In all cases the attitudes of the relict foliation are parallel to those of the schists bordering the granitic rocks on the east.

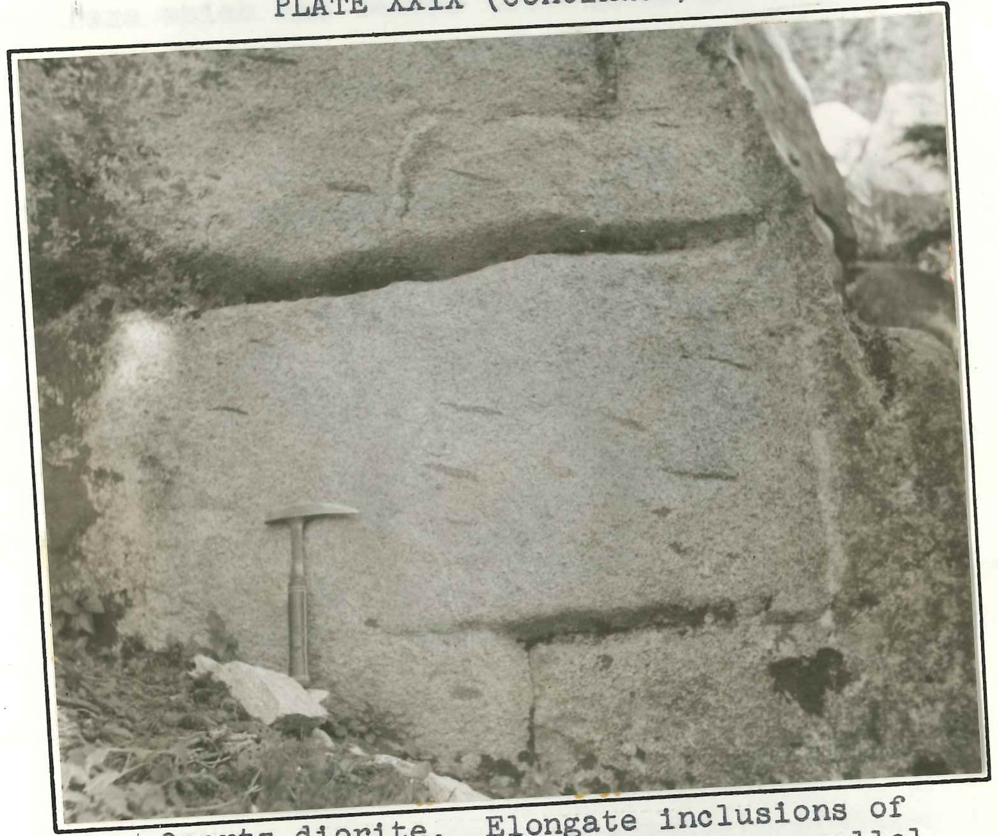
In addition to the relict foliation, dark inclusions in varying states of transformation are frequently found. Nowhere can a mass of granitic rock more than a few feet across be found that lacks these inclusions (Plate XXIX, A). The materials forming most of the inclusions vary from slightly hornfelsized schists to shadowy remnants or skialiths. There also are occasional inclusions of lenticular quartz masses, up to several inches in length, which are identical in shape and composition to the elongate quartz bodies so common in the biotite-quartz schists. These quartz inclusions contain elongate biotite plates in parallel orientation. Another type of inclusion which is fairly common, especially in the vicinity of Lake Valhalla, consists of lenticular aggregates or attenuated stringers composed of at least 95 per cent biotite. These vary in length from one inch to several feet.

Most of the various types of elongate inclusions occur singly or in small groups. When found in groups they display a striking parallel arrangement (Plate XXIX, B), and their orientation was found to be parallel to the attitudes of the schists and gneisses on the east, even where the inclusions measured are as much as five miles distant from the contact of

PLATE XXIX

A. Leucocratic quartz dioritic rock with inclusion of hornfelsized and felspathized schist material. Southwest of Lake Valhalla (spec. B-3).

PLATE XXIX (continued)



B. Quartz diorite. Elongate inclusions of hornfelsized schist material in parallel arrangement. Attitudes identical to those of adjacent schists. Southwest of Lake Valhalla.

the granitic rocks and the schists.

At places the inclusions are not elongate in shape, and they show a random orientation and signs of rotation (Plate XXV). Such zones of inclusions are interpreted as schist areas which had become brecciated and subsequently were invaded by granitic materials.

The many inclusions of schists found within these granitic rocks vary considerably in texture and degree of transformation into more granitic rocks. Some of them are composed of schist which is unaltered except for a superimposed slight hornfelsic texture. Others are mere shadowy relics or skialiths which differ only slightly in texture and composition from the enclosing granitic rocks. In most cases the contact between the inclusion and enclosing granitic rock is transitional (Plate XXIX, A). Where the contact is sharp (and this is quite uncommon) there is usually a 0.5 to 2.0 mm wide selvage of biotite around the inclusion.

Many of the only slightly altered inclusions of schist have the following approximate composition: 25 per cent biotite, 25 per cent actinolitic hornblende or green hornblende, 25 per cent plagioclase, 10 per cent quartz, and accessories. Megascopically this type of inclusion often appears schistose, consisting of alternating lighter and darker bands. Microscopic examination shows, however, that the biotite and hornblende have predominantly lost their elongate shape and their parallel orientation due to a superimposed static recrystallization. Frequently the original structure of the schist is still visible as a relic in the form of parallel bands of graphite running through the mafic crystals. Some of the biotite and hornblende have remained elongate, and some polygonal arcs similar to those of adjacent schists have been preserved as relics. Usually there is evidence that hornblende was once the dominant mafic, and that extensive biotitization has occurred. Part of the plagioclase of the inclusions has the same composition as the plagioclase of the surrounding granitic rock but is of a much smaller grain size. Part of the plagioclase of the mafic-rich inclusion is somewhat more sodic than the plagioclase of the adjacent granitic material. Accessory minerals, such as apatite, sphene, magnetite, and occasional garnet, are the same in the inclusions and the granitic rock.

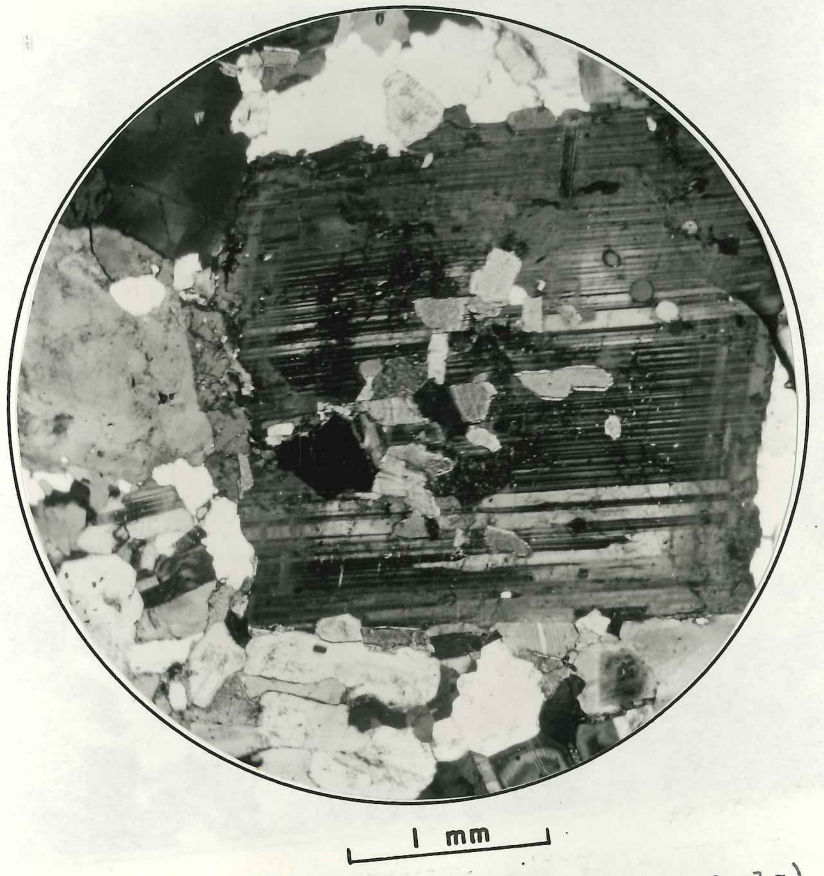
Regular jointing is very common in the granitic rocks. Normally there are three sets of joints, roughly at right angles to each other, but apparently without a consistent orientation throughout the area.

Petrography. The bulk of the rocks forming the main granitic body are medium-grained and leucocratic with a completely crystalloblastic texture. All mineral constituents are anhedral, very irregular in outline, and interlock one with another. The dominant minerals are plagioclase, quartz, biotite, and hornblende, with subordinate microcline. Apatite, sphene, orthite, magnetite, and occasional garnet are accessories, and epidote, clinozoisite, muscovite, and sericite have formed through secondary processes.

Plagioclase usually forms 50 to 60 per cent of the rock. The plagioclase crystals vary in size from minute, 0.1 to 0.2 mm rounded grains, to a maximum of 4.0 mm. The average is 2.0 mm in size. The plagioclase is generally twinned after the albite and carlsbad laws, though pericline twinning is also found. Complex zoning may occur in some of the larger crystals. The average composition of the plagioclase is about Ab_{70}, with variations from Ab_{60} to Ab_{75}.

Strain shadows are common in the plagioclase, and the crystals are often bent, frequently in an undulating fashion. Examples of fracturing of plagioclase grains and of healing by plagioclase substance are often found. Most of the plagioclase crystals contain numerous inclusions of biotite, hornblende, and quartz (Plate XXX, A). Retrogressive sericite, epidote, and clinozoisite may also be present in the plagioclase. The sericite has clouded many of the crystal centers and obliterated the twinning. Only the smaller plagioclase crystals which have formed in the intergranular spaces are clear. Frequently plagioclase has penetrated biotite and hornblende grains along their cleavage planes. Some plagioclase grains have pushed aside and bent out larger elongate grains of

PLATE XXX



A. (Photomicrograph, crossed nichols) Oligoclase porphyroblast. Inclusions of biotite, epidote, chlorite, and quartz. Lake Valhalla (spec. B-2).

PLATE XXX (continued)

B. (Photomicrograph, crossed nichols) Sodic oligoclase porphyroblast growing in groundmass of biotite, muscovite, and quartz. Inclusion of twinned calcic oligoclase (top). Quartz diorite. Lake Valhalla (spec. B-2).

biotite and hornblende.

Where hornblende is a major constituent the plagioclase is somewhat more calcic in composition. The same applies to rocks which originally possessed a high hornblende content but in which the hornblende has been extensively biotitized. More sodic plagioclase is found where biotite was the original mafic, or where a later stage of plagioclase growth has occurred (Plate XXX, B). Some of the larger plagioclase crystals show cloudy, more calcic centers with more sodic rims.

Quartz generally forms about 10 per cent of the rock, and exceptionally rises to 25 per cent. Like the plagioclase, the quartz occurs in irregular grains with crenulated borders characteristic of crystalloblastic growth. Several generations of quartz appear to be present. One generation apparently predates the plagioclase inasmuch as it is replaced and often engulfed by the plagioclase. To the same first generation are assigned occasional lenticular areas of a fine-grained quartz mosaic, up to one centimeter in length, which enclose elongated flakes of biotite in parallel orientation. These quartz patches bear a striking resemblance to the fine-grained, quartz-rich bands and lenticles commonly found in the biotite-quartz and biotite-hornblende-quartz schists.

An intermediate generation of quartz appears to be contemporaneous with the growth of the bulk of the plagioclase. In several instances the outlines of small, subrounded quartz grains of the quartz mosaics (cf., above) occur as relics within a later-formed, larger quartz crystal of markedly different orientation. In addition, many of the biotite and hornblende crystals penetrated by the plagioclase are also invaded by quartz lying adjacent to the plagioclase. This intermediate generation of quartz is very conspicuous in those hornblende-rich rocks which were originally very low in quartz (cf., pages 34 and 35).

The latest generation of quartz fills minute fractures, up to 4 mm in width, which transect the rock, and this quartz is invariably associated with a vermicular growth of quartz and feldspar to be described below. In some cases this quartz appears to have grown into and to have wedged apart large crystals of plagioclase.

A vermicular growth of quartz and feldspar is often found in maggot-like patches along narrow, elongate zones. Adjacent to these zones are quartz and plagioclase crystals showing strain shadows, snipped-off ends, and mortar structure. This suggests that the vermicular growth has taken place during a process of recrystallization occurring in minute fracture zones. Usually these zones do not exceed 2 mm in width, though a maximum of 4 mm is exceptionally attained.

As in the case of the gneisses farther to the east (cf., page 51) this vermicular growth of quartz and plagioclase always occurs adjacent to microcline which encroaches upon and often engulfs pre-existing plagioclase and quartz grains. Some of these microcline crystals may attain a size of 4 mm, but less than half of this is the rule. In a few cases microcline forms as much as 10 per cent of the rock and then equals quartz as a major constituent; but a microcline content of 5 per cent or less is far more common.

In these recrystallized minute fracture zones the newly-formed, usually small plagioclase grains are more sodic than the plagioclase of the main rock. Their usual composition is Ab_{75}. The recrystallized quartz in such zones grows into the larger, earlier plagioclase crystals bordering these fractures.

This growth of microcline and quartz, in addition to plagioclase, implies that potassium and silica were introduced during the recrystallization of these late fracture zones.

Mafics compose up to 20 per cent of the rock. They are rarely evenly-distributed in the rock but generally form irregularly-shaped and irregularly-distributed clusters (Plates XXVII, B, and XXVIII, A and B).

Biotite is usually dominant and forms irregular plates averaging 1 to 2 mm in size. In the biotite there is a strong development of pleochroic haloes around zircon nuclei which recalls similar phenomena in the schists. Small magnetite grains are frequent inclusions in the biotite. The biotite crystals are often bent and gently folded and some show minute fractures, some of which have only partially been healed. Chloritization of the biotite along its cleavage planes is common, especially in more weathered specimens, and muscovite and sericite are additional products of the alteration of biotite.

The other mafic of major importance is either actinolitic hornblende or, less frequently, common green hornblende. The actinolitic hornblende is identical with that previously described from the schists, and its quantity occasionally exceeds that of the biotite in the granitic rock. The hornblende occurs in irregular grains up to 5 mm in size, although most crystals do not exceed 2 mm. It is usually more or less biotitized, and in a few examples biotitization has almost eliminated hornblende from the rock. Most of the biotite is obviously derived from the hornblende. Small, rounded grains of magnetite associated with and often included in the biotite are interpreted as having formed during the biotitization of hornblende to accommodate some of the released iron. This biotitization of the hornblende indicates that an introduction of potassium occurred at an earlier stage than the more local, late introduction which caused microcline to form (cf., pages 75 and 76).

It has been emphasized that the mafics in these granitic rocks commonly form unevenly-distributed irregular clusters. In most cases these patches lack preferred orientation.

However, at some places a parallel orientation of the mafics does occur (Plates XXVII, B, and XXVIII, A and B). Many rocks, megascopically directionless, contain gently curved polygonal arcs of biotite and hornblende. In addition, there are large areas, such as the ridge of Barrier Peak (Plate A), where an alternation of lighter and darker bands varying in their proportion of mafics gives the rock a gneissose appearance. This structure is due to a compositional variation rather than a preferred orientation of the individual mineral constituents. It is noteworthy that on Barrier Peak, and in other similar areas, the gneissose structures have attitudes parallel not only to those of closely adjacent inclusions of hornfelsized schists but also to the trend of the main schist body lying east of the granitic rocks.

Accessory minerals in the granitic rocks are orthite, sphene, apatite, and occasional garnet. Epidote, clinozoisite, muscovite, and sericite are frequently found as secondary minerals in and around plagioclase and biotite. Part of these secondary minerals probably are retrogressive and formed during a time of falling temperatures, and part may be the result of weathering. There is a conspicuous similarity between the accessory minerals of these granitic rocks and the accessory minerals of the schists and gneisses previously described (cf., pages 35, 49, and 50).

The bulk of the granitic rocks in this area can be called leucocratic quartz diorites. Quartz-poor varieties may be called quartz-bearing diorites. Local varieties in which microcline makes up as much as 10 per cent of the rock approach a trondhjemite in composition.

Description of the Migmatitic Border Zones

The granitic rocks are everywhere in gradational contact with the schists, with the one exception of the ridge of Mt. Fernow (cf., page 60). However, regardless of the type of contact, the border zones of the granitic body display all variations between relatively uniform, mostly directionless granitic rocks and partly directional, partly directionless migmatites composed of schists and granitic rocks.

Proceeding from the main granitic body towards a contact with the schist, the inclusions, which in the main body usually form amounts of less than 2 per cent, become more and more abundant, and finally an area of dominant schist is reached. These mixed border zones vary from a hundred yards to as much as a mile in width. Since in these migmatitic zones there exist all gradations between and all proportions of granitic and schist material, it is impossible to single out one specimen or one small area as being typical. However, regardless of their position within the migmatite zones, the rocks in these zones do possess certain common characteristics.

1. The contacts between the relatively coarse-grained, leucocratic granitic rocks and the much more fine-grained, darker schists are usually gradational. This applies, regardless of whether the schist is a small, blocky or rounded inclusion within the granitic rock, a layer intercalated in the granitic material, or spatially continuous with the main schist area.

2. Though the schist material in the migmatitic border zones megascopically resembles the rocks found in the main, uniform schist area, it generally displays a superimposed hornfelsic microtexture, especially so in schist inclusions which are surrounded by granitic material. Relict schistosity and occasional polygonal arcs have, in the majority of cases, been preserved in the schist materials, but most of the mafics have recrystallized into irregularly-shaped and haphazardly-oriented grains, some of which enclose thin bands of graphite marking the original schistosity. In many cases the schistosity has been lost, especially in the more strongly transformed inclusions of skialith-type.

3. With the hornfelsic texture there is always associated a growth of small plagioclase grains, usually of a somewhat more sodic composition than the larger plagioclase crystals found in the adjacent granitic rocks. At the same time the amount of quartz has increased; this increment is particularly conspicuous where the original rock was a quartz-poor

hornblende schist or amphibolite. During this metasomatic plagioclase and quartz growth, elongate biotite and hornblende crystals were included along the twinning planes of plagioclase and were invaded and engulfed by plagioclase and, less frequently, quartz.

The superimposed hornfelsic texture, and the increase in plagioclase and quartz observed in the schist material within the migmatite zone, gradually disappear with increasing distance from the contact between migmatite and schist. A few hundred yards from the contact the schists usually possess a well-marked orientation of their mafic constituents.

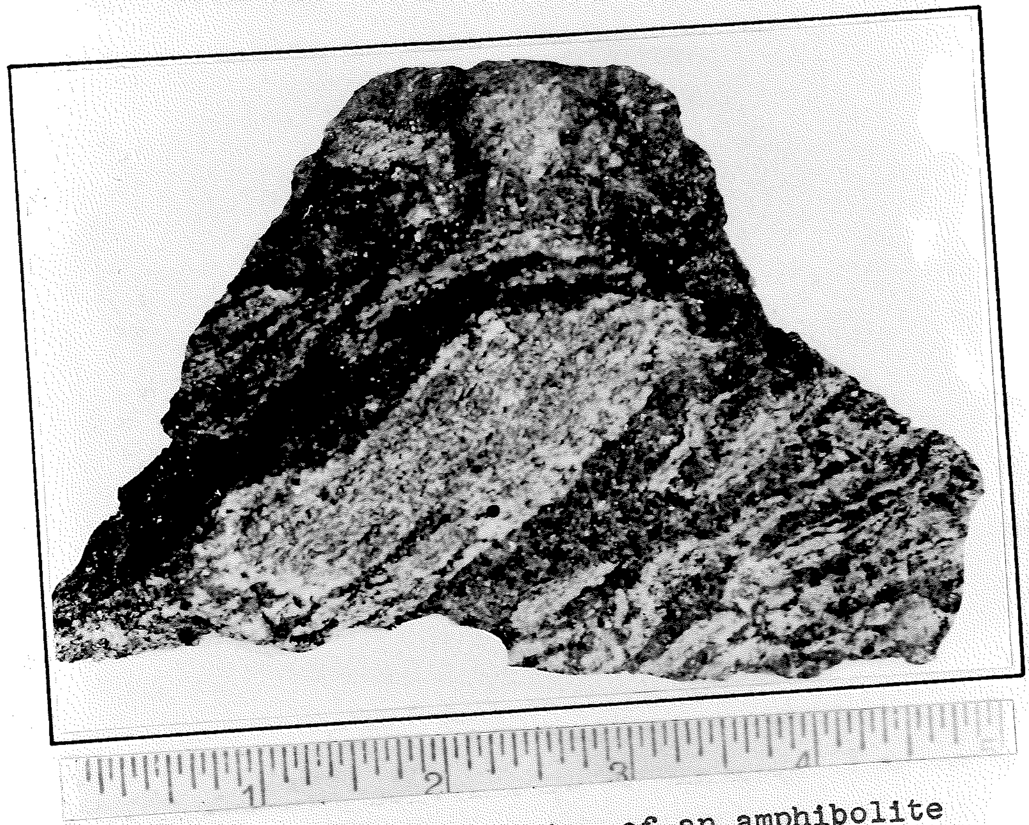
4. The granitic rocks of the migmatite zones vary in composition and texture. The specific variety of granitic rock produced appears to depend upon the variety of schist which was invaded, and upon the degree of felspathization and transformation of this schist material. Where biotite-quartz or biotite-hornblende-quartz schists have been transformed into granitic rock, a leucocratic quartz dioritic rock has resulted. Where an amphibolite was the country rock, a dark dioritic rock has been formed (Plate XXXI). The latter variety is especially common along Nason Creek where schists rich in actinolitic hornblende and common green hornblende have been infiltrated by granitic materials (Plate XXXII).

5. One fact concerning the migmatite zones must be emphasized. With but one exception (cf., page 60) there is no

PLATE XXXI

Migmatite. Felspathized amphibolite. Textural and compositional variation from a dioritic rock to a hornfelsized amphibolite. Nason Creek, near confluence with Mill Creek (spec. C-1d).

PLATE XXXII



Migmatite. Felspathization of an amphibolite along the planes of relict foliation. Road cut, one mile northwest of confluence of Mill and Nason Creeks (spec. 6-22-9-49).

evidence of forcible intrusion of the schists by granitic materials. There is no evidence of magmatic flow structure, regardless of whether the granitic material is intercalated in the schists or, as is more often the case, transects the schists in vein and dike-like irregular masses. No dilation effects have been observed. A static invasion of the schists by granitic materials is indicated by the many discontinuous but aligned layers of schist material lying within the granitic rocks, and the frequent folded relict structure marked by alternations of lighter and darker bands (Plate XXXIII).

Rotated schist blocks with random orientation are common, but the migmatite zones containing these rotated blocks are interpreted as being replacement breccias, and the rotation of their schist blocks is attributed to pre-granitic tectonic brecciation. This interpretation of replacement breccias formed by incomplete static granitization of previously brecciated schists is strongly suggested by the following features:

a. There is no evidence of magmatic flow structure (cf., page 81).

b. All textures in schist materials and granitic rocks are crystalloblastic.

c. The migmatite zones contain many large, shadowy blocks with hornfelsized schist centers which show a complete gradation between a relatively coarse-grained granitic rock and a much finer-grained hornfelsized

PLATE XXXIII

Migmatite zone. Relict folds preserved in granitoid rock by alternations of darker and lighter bands. Layer of hornfelsized and felspathized schist material (s). Post-granitic quartz and feldspar pegmatite (p). North slope of Mt. Fernow.

schist (Plate XXXIV).

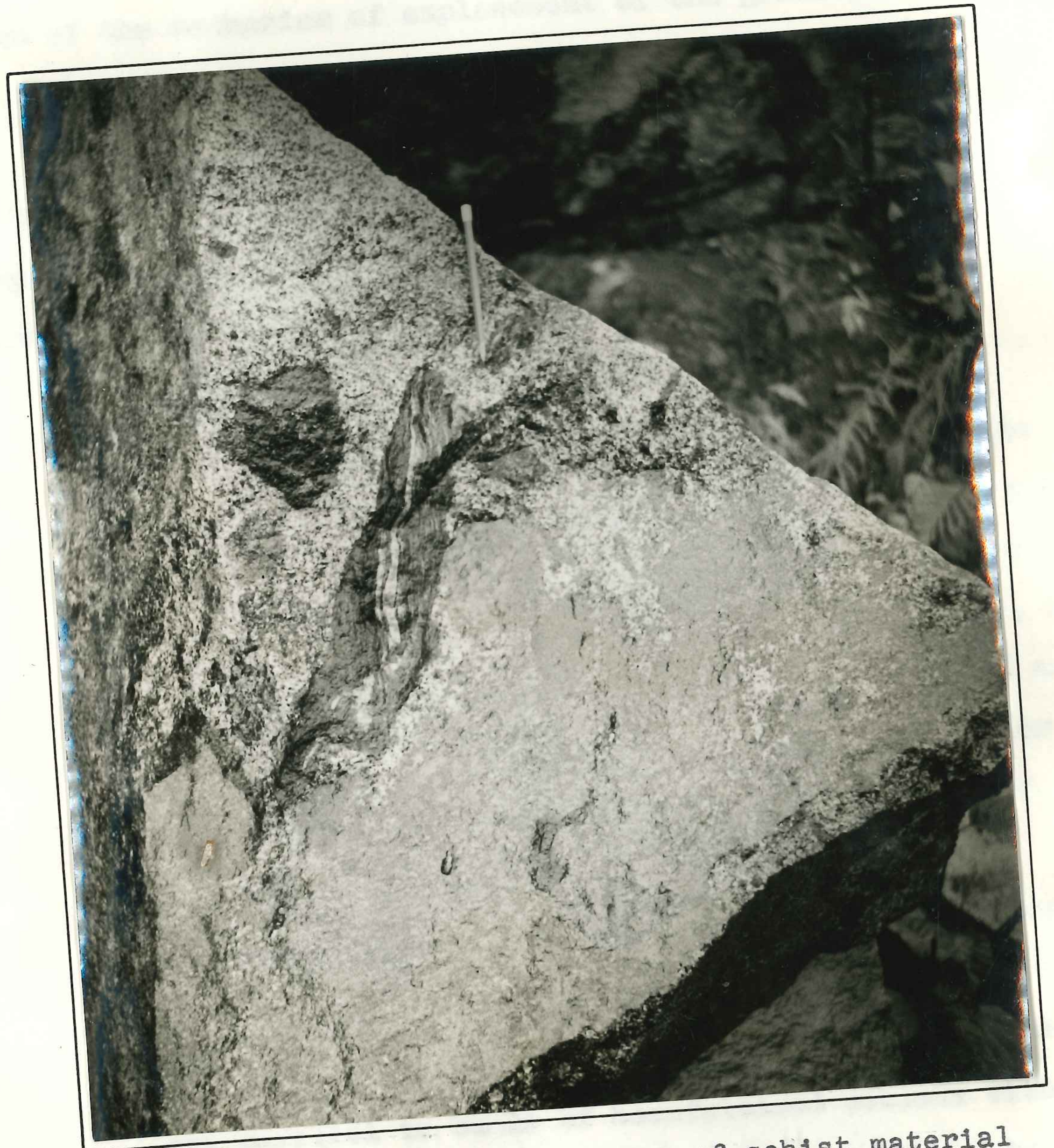
d. Stringers of mafic materials can be frequently seen extending from partially transformed schist blocks into the granitic rocks, and sometimes these stringers extend completely across the dike-like granitic bodies.

Genetic Interpretation

The field and petrographic evidence presented is interpreted as indicating that the bulk of the granitoid rocks found in the Stevens Pass area have been formed by the metasomatism of pre-existing schists and amphibolitic rocks. It has been pointed out above (cf., pages 75, 77, 81) that there is evidence for an introduction of sodium, potassium, and silica which caused the isochemically-metamorphosed rocks, most of which contained hornblende, to be changed in texture, structure, and composition to predominantly quartz dioritic granular rocks (cf., pages 51-53 for a detailed discussion of similar metasomatic processes).

This conclusion applies to the entire granitic area thus far mapped, except for the granitoid rocks occurring along the ridge of Mt. Fernow. It is on Mt. Fernow alone that a sharp and discordant contact of schist and granitoid rock was found. Here also occurs an abrupt change in the prevailing strike of the schists (Plate B) which, coupled with the sharp contact, may indicate that at this locality the granitic rocks

PLATE XXXIV



Replacement breccia. Inclusions of schist material vary in degree of transformation from hornfelsized biotite-quartz schist to skialiths. Dark inclusion to the left of the biotite-quartz schist is a segregation of mafic minerals. Lower Mill Creek.

have forcibly intruded the schists. However, further field and petrographic study is necessary before a valid interpretation of the mechanism of emplacement of the granitoid rocks of Mt. Fernow can be made.

In all other areas there is evidence for a metasomatic origin of the granitic rocks. This evidence has been presented above in the descriptions of the rocks and may be summarized as follows:

1. Field evidence:
   a. The contacts between granitic rocks and schists are extremely gradational and are accompanied by wide migmatitic zones in which all kinds of transitions between schists, various types of gneissose rocks, and directionless granitic rocks occur (cf., pages 58 and 79). Similar transitions are found in the interior portions of the granitic body where inclusions and relict bands of schist occur.
   b. Many of the schist inclusions found in the interior parts of the granitic body, often miles from the migmatitic border zones (cf., page 66), are aligned and are parallel to bands of hornfelsized schists within the granitic body. Both schist inclusions and bands are parallel to the strike and dip of the schist adjacent to the granitic body. The lack of disturbance of these relict schist inclusions and layers appears to

preclude emplacement of the granitic body by forceful injection of the country rock.

c. Relict foliation occurs, both in the migmatitic border zones and in the interior portions of the granitic body. It is parallel to the strike of the schist adjacent to the granitic body (cf., pages 66, 78, and 86).

d. Neither in the migmatitic border zones, nor where schist material occurs in the interior of the granitic body, were any structures seen which would indicate forcible intrusion or dilation (cf., page 81).

2. Petrographic evidence:

a. The textures of the various granitoid rock types are entirely crystalloblastic (cf., page 70, etc.). The growth of plagioclase and quartz, at the expense of and around pre-existing minerals, is especially conspicuous, suggesting replacement.

b. The granitoid rocks conspicuously lack a uniform composition, chemically, structurally, or texturally (cf., pages 63, 75, 77, and 81). Layers and inclusions of schist material, and unevenly-distributed patches of mafic minerals, emphasize this heterogeneity.

c. The type of granitoid rock is apparently determined by the type of schist replaced. There is a definite association of dioritic types with hornblende-rich schists, and of quartz dioritic types with biotite-hornblende-quartz schists (cf., page 81).

d. Relict schistosity and occasional polygonal arcs of biotite and hornblende are common to both hornfelsized schists and granitic rocks (cf., page 78).

e. Both the relict inclusions and the surrounding granitic rocks have accessory minerals usually identical in quantity and type (cf., page 70).

f. The mafic minerals of the relict schist material and the surrounding granitoid rocks are of identical composition (cf., page 77).

g. The plagioclase of the hornfelsized schists and of the granitic rocks varies in a similar manner, being more calcic in the presence of hornblende, and more sodic in the presence of biotite as the original mafic mineral (cf., pages 74 and 81).

From a chemical point of view, the essential difference between the schist material and the granitic rocks is an addition of sodium and silica and minor potassium to the granitic rock which has led to an increase in plagioclase and quartz, to the biotitization of part of the hornblende, and to a more local development of late microcline.

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